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THE CORRELATION BETWEEN RAINFALL AND NORMALIZED DIFFERENCE VEGETATIVE INDEX IN EAST AFRICA

ABSTRACT

Captain Michael L. Davenport
The Florida State University, 1987

Major Professor: Sharon Nicholson, Ph.D.

Vegetation dynamics, as measured by the Normalized Difference Vegetative Index (NDVI), and monthly rainfall are compared at seventy-eight stations in East Africa to determine spatial and temporal relationships between moisture and vegetation response. Rainfall and NDVI are found to be coincident in both space and time; with highest NDVI values persisting from year to year in areas of maximum rainfall. Large changes in monthly rainfall from one year to the next result in large NDVI changes. Due to the spatial variability of vegetation types in East Africa and the varying NDVI response of vegetation to moisture, correlations of monthly-integrated NDVI and monthly are performed by plant zone. To determine the time lag between rainfall and resulting NDVI change, NDVI is regressed against averages of rainfall of previous months. The combination giving the highest coefficient of correlation is used to quantify the time lag between rain and NDVI response. Monthly-integrated NDVI and monthly rainfall of the stations within a single plant zone correlate well. When the three-year averages of yearly-integrated NDVI and yearly rainfall are compared, a strong relationship is obtained (r=.76). This relationship could provide a means of estimating annual rainfall over data sparse regions. An improved vegetative mapping scheme is devised and applied to the three-year average of the data. The mapping scheme results in a mapping that is far superior to previous mappings using NDVI data.

Keywords: theses; (KR).

THE FLORIDA STATE UNIVERSITY

COLLEGE OF ARTS AND SCIENCES

THE CORRELATION BETWEEN RAINFALL AND NORMALIZED DIFFERENCE VEGETATIVE INDEX IN EASTERN AFRICA

by

MICHAEL LEROY DAVENPORT

A Thesis submitted to the
Department of Meteorology
in partial fulfillment of the
requirements of the degree of
Master of Science

Approved:

Professor Directing Thesis

Fall Semester, 1987

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1. INTRODUCTION

Beginning in the early 1960's, the increasing use of the satellite remote sensing platform, in concert with advances in computer technology, has fueled expanded research in many scientific fields - including those of meteorology and biology. More recently, with the establishment of several seminal relationships between satellite data and the physical characteristics of plant life, expanding emphasis has been placed on the satellite as a tool for the monitoring of the dynamics of plant life. For years, biologists have designed experiments to show the relationships between plants and the environment; however, research of this type has been limited mainly to crops or to small groups of a single species in a laboratory setting. The logistics involved with a comprehensive sampling of an entire plant zone - with a spatial scale of hundreds to thousands of square kilometers - preclude a test of this type. The satellite remote sensor provides researchers with the ability to accurately determine vegetation characteristics over large areas of the earth's surface, and will allow comparisons of vegetation and environmental variables on a scale not before possible.

The purpose of this study is to determine the relationship between plant greenness and rainfall in Eastern Africa. The relationship between rainfall and plant greenness will be examined

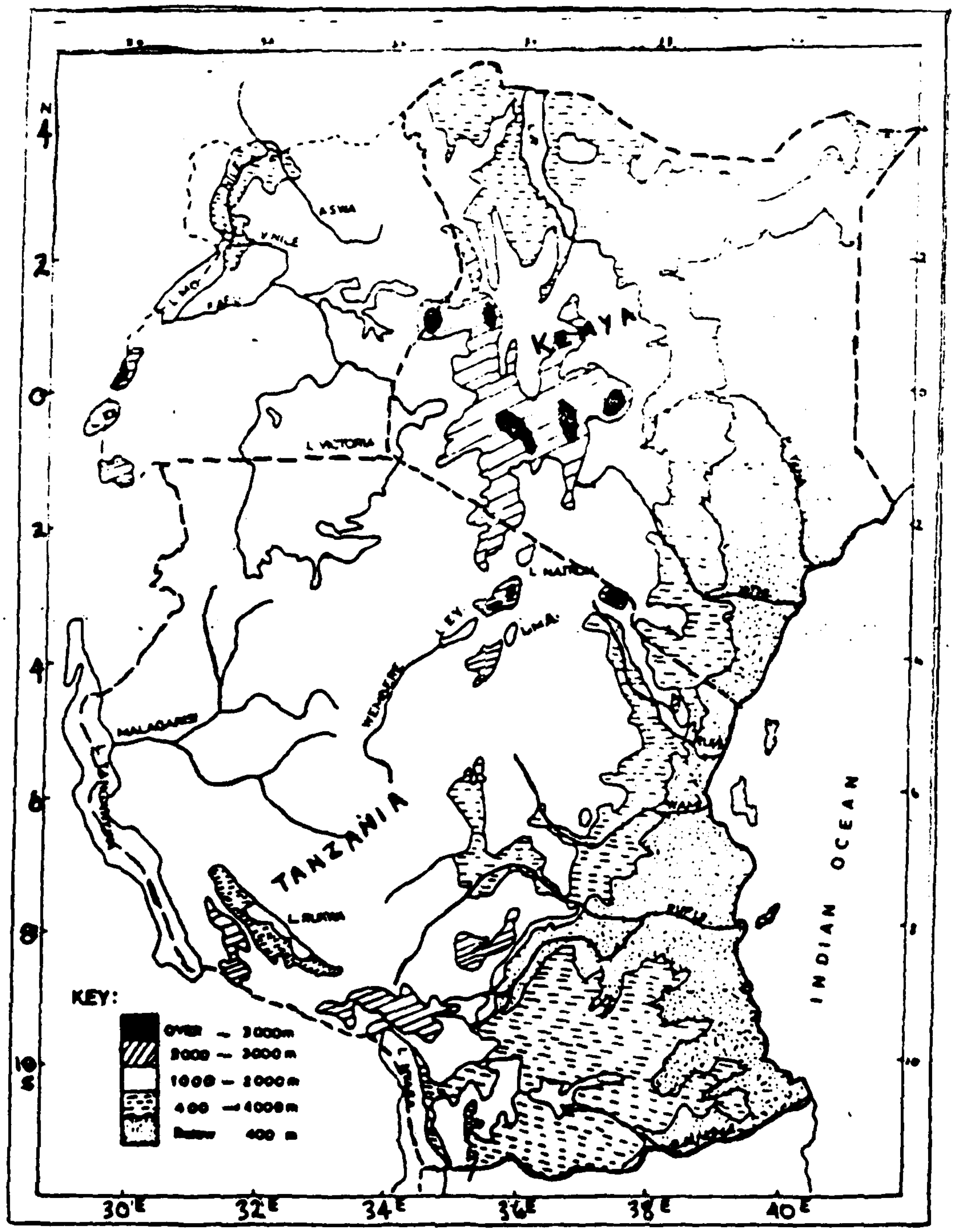
for spatial and temporal patterns, and will be quantified for stations in previously determined vegetation zones. In order to better understand the many topics in this work that will be unfamiliar to most meteorologists, this paper begins with a short description of the geography and rainfall climatology of East Africa. The effect of the atmosphere on plant life is briefly presented, the theory and mechanics of satellite remote-sensing of vegetation is discussed, and the most seminal related research will be presented.

1.1 GEOGRAPHY AND CLIMATOLOGY

The countries of Tanzania and Kenya, hereafter referred to as East Africa, lie between 5^0N and 12^0S latitude on the east coast of Africa. The interior of the region is dominated by highland regions and plateaus with isolated mountain peaks reaching over 6000m. Large inland lakes found in the Great Rift Valley bisect Kenya and comprise much of the western border of Tanzania. Figure 1.1.1 shows the geography of the region, and highlights the upland regions and major bodies of water.

Although East Africa straddles the equator, rainfall seasonality at many locations is not characterized by distinct wet and dry seasons; nor is the area as rainy as its equatorial position would indicate (figure 1.1.2). Evapotranspiration is unrelentingly high throughout the year at all but high mountain stations, and exceeds rainfall at most locations during much of the year. Figure 1.1.3 shows average monthly evapotranspiration throughout East Africa.

Figure 1.1.1. Physical Features of East Africa (From Nyenzi, 1979).



The rainfall of the region is driven by the seasonal movement of the Intertropical Convergence Zone (ITCZ), but is highly modified by orography, large inland water sources and seasonal influxes of moist low-level westerlies (Ogallo, 1984). Stations near the coast at low elevations exhibit more distinct wet and dry seasons, although yearly rainfall totals are lower than would be expected for a station at these latitudes. The abnormally low rainfall amounts occurring at most East African stations are the result of many factors, including cold upwelling currents to the north of the Kenyan coast, the drying effects of Madagascar on the otherwise moist southeasterly flow, and

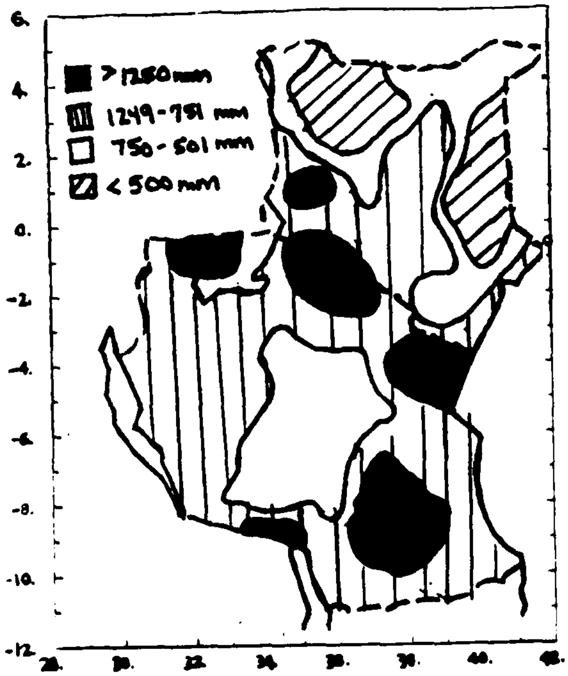


Figure 1.1.2. Average annual rainfall in East Africa

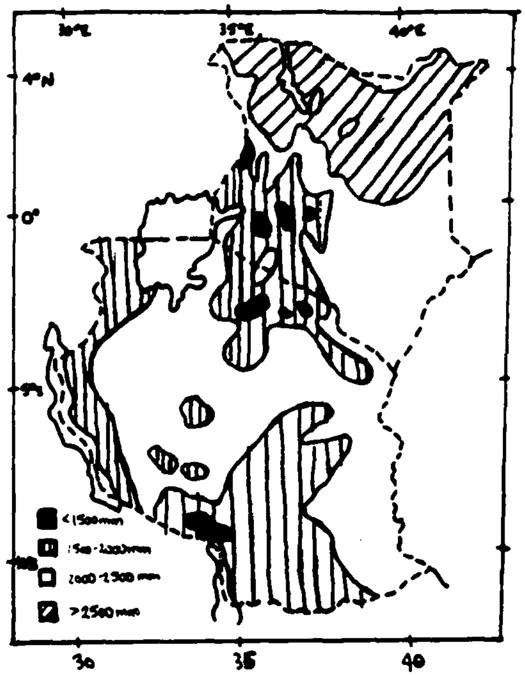


Figure 1.1.3. Average annual potential evapotranspiration in East Africa (From Griffiths, 1972)

the "rain-shadow" effect of the coastal hills and mountains of East Africa.

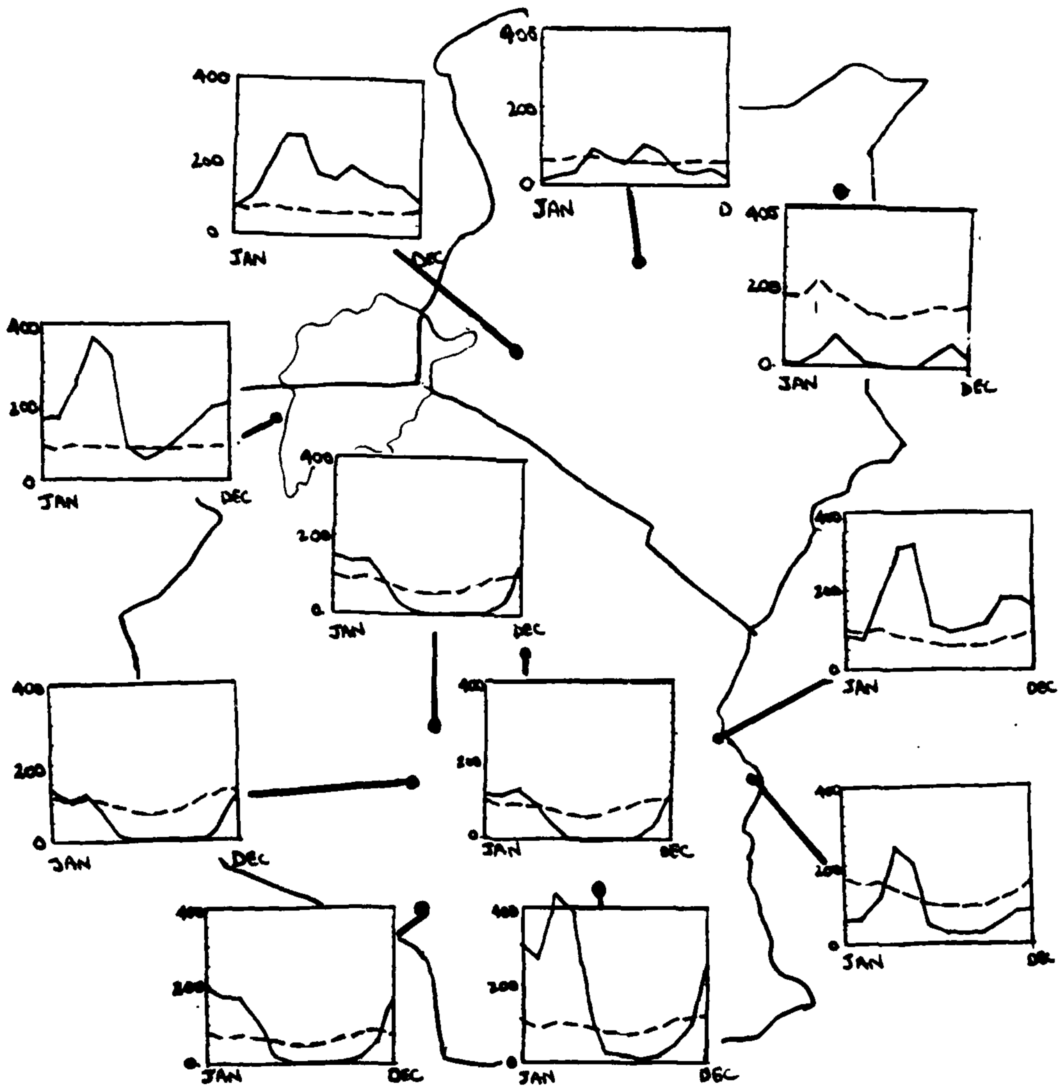


Figure 1.1.4. Average monthly rainfall and potential evapotranspiration at stations in East Africa. Solid line represents rainfall, dashed line represents potential evapotranspiration. Vertical axis is rainfall and potential evapotranspiration, horizontal axis is time.

Rainfall seasonality - the timing and duration of rainy and dry periods - is very complex (Kenworthy and Glover, 1958). Near the equator, rainfall is bimodal in nature (two wet and two dry periods per year). With increasing distance from the equator, yearly rainfall transitions towards unimodal seasonality - becoming unimodal across much of southern Tanzania. Trimodal rainfall distribution, the result of invasions of moist low-level westerlies from the Congo basin, is found in western parts of Kenya and Tanzania (Ogallo, 1984). The distinctness of wet and dry seasons decreases in the highland regions, on the western shore of Lake Victoria (see figure 1.1.4).

Rainfall is erratic and unreliable from year to year, especially in the most arid portions of East Africa. The coefficient of variation (standard deviation/mean) is high for most stations in the region (see table 2.1) indicating a large year-to-year variability of rainfall. For comparision, typical annual values of coefficient of variation range from .10 in humid regions to around .50 in semi-desert regions. Rainfall amounts sufficient for crop growth are consistently received (e.g., received at least four years of five) in very limited locations in Kenya and Tanzania. In addition to being variable in time, the East African rainfall is highly variable in space. Both long-term (large scale circulation and local influences on rainfall) and short-term (cellular structure of convection and high positive skew associated with typical rainfall) influences control the spatial variation of rainfall (Nicholson, 1986).

1.2 ENVIRONMENTAL EFFECTS ON PLANT GROWTH

It has been shown that when all other factors are kept constant, increased soil moisture results in increased plant growth (Le Houérou, 1984). Although no single physical factor is solely responsible for controlling plant growth, it is believed that below elevations of 2000 m in East Africa, rainfall is the dominant determining factor in plant growth and plant distribution (Langdale- Brown and Wilson, 1964).

Perhaps as important as the rainfall amount received is the rate at which rain falls. Obviously, a centimeter of rain falling over several hours will be more easily assimilated into the soil for later use by the plant than the same centimeter falling in a few minutes, much of which will be lost to surface runoff. With the exception of the cloud belts of the mountain region, most of the precipitation in East Africa is convective in nature, with resulting high rainfall rates. Many other climatological and physical factors influence plant growth. Extreme temperatures and humidities can effect plant growth and respiration. For example, high nighttime air temperatures have been shown to decrease plant growth due to the inhibition of the carbon-fixing process within the plant. Soils are likewise important to plant growth and distribution. A soil type can extend or restrict the spatial distribution of plant types independent of rainfall. In general, the chemical composition, fertility, and efficiency of absorbing and storing water are means by which soils impact plant growth and distribution.

Finally, the influence of civilization on the environment in East Africa is phenomenal. Langdale-Brown and Wilson (1964) estimated that less than 4% of the neighboring country of Uganda remained in its naturally vegetated form in 1960. Fertile soils are intensively farmed, grazing of livestock is heavy over much of the remainder of the region, and fire is widely utilized to speed the return of nutrients to the soil. All have a predictable effect on native and introduced plant growth.

1.3 REMOTE SENSING OF VEGETATION

During the past decade earth scientists have realized the utility of satellite remote sensing as a means to sample large areas of the earth's surface in an accurate and timely manner. Although research in the application of remotely sensed satellite data to plant systems is relatively new, much has already been accomplished in terms of the measurement of biophysical conditions, and inventory and classification of the surface of the earth.

Although satellites were in use in the early 1960's, the first satellite tailored for land surface research, the LANDSAT 1, was not operational until 1972. Since that time, four more LANDSAT satellites have been launched, as well as five "for other use" satellites that have been applied to the task of remote sensing of vegetation. Characteristics of the operational satellites are shown in table 1.3 below.

In studies where high spatial resolution is critical, LANDSAT Multispectral Scanner (MSS) data is used, where the higher resolution

	CZCS*	AVHRR†		MSS‡	
	Nimbus-7	NOAA-6,8#	NOAA-7,9	Landsat 1–3	Landsat 4,5
Visible/near-infrared bands	5	2	2	4	4
Orbit altitude	955 km	850 km	850 km	920 km	705 km
Equator crossing	12:00	7:30	14:30	9:30	9:30
Nadir ground resolution	825 m^2	1100 m^2	1100 m^2	79 m^2	83 m^2
Swath width	1566 km	2700 km	2700 km	185 km	185 km
Field of view	±39°	±56°	±56°	±5.5°	±7°
Effective repeat coverage	6 days	2 days	2 days	18 days	16 days

*Coastal zone color scanner.
†Advanced very high resolution radiometer.
‡Multispectral scanner.
#NOAA-8 removed from service, MARCH 1985.

Table 1.3. Characteristics of various satellite sensors (from Roller and Colwell, 1986).

provides much greater accuracy in the identification of ground objects. However, because of the large time period between successive images, the small area covered by each image and the expense of the LANDSAT data (about 1000 times more expensive per unit area of image than the NOAA product), many researchers prefer to use imagery from the NOAA Advanced Very High Resolution Radiometer (AVHRR). The AVHRR obtains data over large areas at frequent intervals. In addition to supplying more data, this allows the detection of rapidly changing surface conditions, such as short-lived plant growth in response to spatially and temporally variable rainfall. The AVHRR also provides a practical means of obtaining cloud-free images because the NOAA satellite images each point on the surface roughly every other day, thereby increasing the probability of a cloud-free image.

The AVHRR measures radiation reflected from the surface in discrete bunches of wavelengths, ranging from the visible range (0.48 μm - 0.68 μm), through the Near-Infrared (NIR) (0.70 μm - 1.10 μm), to the thermal IR range (3.5 μm - 12.5 μm) (Roller and Colwell, 1986). As shown in figure 1.3, incident radiation in the visible

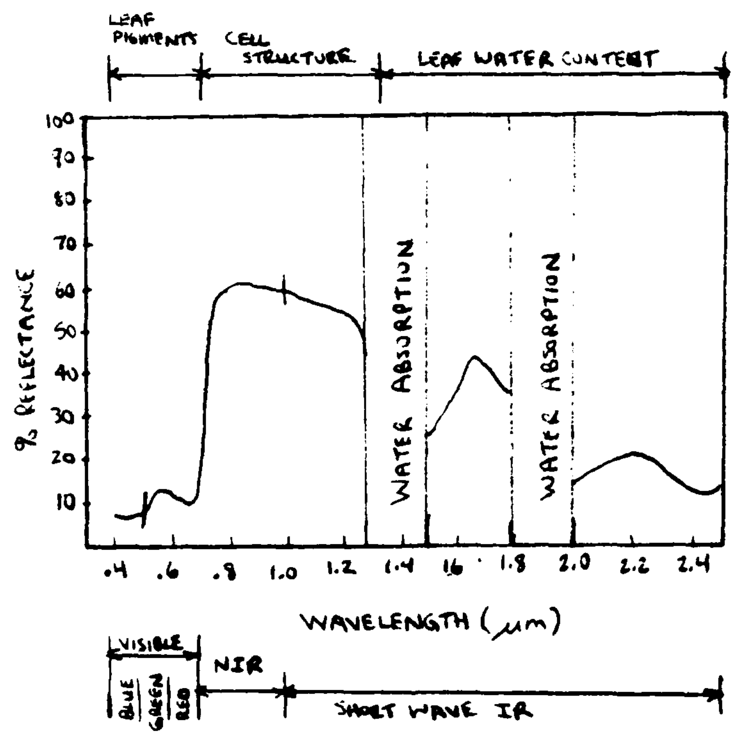


Figure 1.3. A typical vegetative reflectance curve as measured by field spectrometer (from Rock et al., 1986). Top scale indicates the physical factor controlling leaf reflectance.

wavelengths is strongly absorbed by green leaves through scattering and absorption by photosynthetic pigments. The reflection peak

between 0.52 μm and 0.60 μm is due to the green reflection (Rock et al., 1986). The red band absorption represents absorption in the leaf by chlorophyll and is inversely proportional to the chlorophyll density (Tucker et al., 1985a).

Radiation in the NIR is strongly reflected by healthy green leaves. The reflectance of radiation in the NIR is proportional to the green leaf density. Evident in figure 1.3 is the sharp rise in the reflection curve between 0.68 μm and the NIR plateau. This feature is known as the "red-edge", whose position and slope have been directly correlated with leaf chlorophyll concentrations (Rock et al., 1986). Physiological stresses are sometimes reflected in the changing of the chlorophyll and carotenoid concentrations, and are detectable by subtle shifts in the visible and red-edge portions of the reflectance spectra. Water stress may be detectable by the changing reflectance values in the 1.65 μm to 2.20 μm regions (absorption bands for water).

Several ratios of the visible and NIR reflectance values measured by the satellite are used to derive measures of "greenness". The Normalized Difference Vegetative Index (NDVI) compares the reflectance in the visible and NIR wavelengths. NDVI is widely used because it has been shown to be highly correlated with green leaf phytomass (green plant mass), and is thought to reduce the radiance variation caused by variable surface topography and variable sun angle (Justice et al., 1985). It is calculated by this ratio:

$$(NIR-Visual)/(NIR+Visual).$$

Large NDVI values are generally obtained from heavily vegetated areas. For vegetation, the NIR reflectance is large and the visible reflectance is small - resulting in a large difference and a large ratio. NDVI increases with the increase of plant vigor as measured by increasing absorption of photosynthetically-active radiation (PAR), and is therefore a measure of plant productivity. If the amount of PAR is integrated through a growing season, the resultant value corresponds well with total dry matter production (Tucker et al., 1985a). NDVI generally shows high correlation with Leaf Area Index (LAI). LAI is defined as the amount of leaf area above the unit area of ground (m^2/m^2) (Sellers, 1986). The LAI links the structural characteristics of vegetation to the net primary productivity and transpiration (Botkin et al., 1984). In general, until the competition for light becomes limiting (only in very dense jungle vegetation), increasing LAI results in more total photosynthesis, and therefore greater productivity. LAI values between 1 and 7 can be accurately measured from space.

There are problems and limitations inherent in the application of remote sensing of vegetation. First, the NDVI data obtained by the satellite must be calibrated by ground sampling of vegetation, which is costly and difficult to accomplish in many locations around the world. Next, the correlations between NDVI and plant characteristics begin to break down in plant communities with either very high or very low LAI values. This is not a problem for most plant zones; however, in deserts and thickly vegetated jungles NDVI data must be

used with caution. Finally, the geometrical relationships between the satellite, the sun, and the target complicate the acquisition of accurate NDVI data. Nevertheless, a large number of recent studies have shown the usefulness of remote sensing in studying vegetation.

The US Forest Service, in conjunction with NASA, showed that automated interpretation of LANDSAT could distinguish hardwood forest, softwood forest, and grassland at 70% accuracy or better (Botkin et al., 1984). Tucker et al.(1985b), using 19 months of AVHRR data collected for the continent of Africa, developed a general land-cover classification scheme based on satellite NDVI data. The scheme produced vegetation maps that, in general, correlate with existing vegetation maps of Africa created by land survey. The frequently collected NDVI data was integrated over the 19-month period to obtain an estimate of yearly primary production. The primary production data grouped via principal component analysis allowed the authors to create a continental-scale mapping of the major African plant zones. No attempt was made to differentiate between the "sub-communities" (i.e., between different type of forest).

Tucker et al. (1983, 1985a) are investigating the interrelationships between the land surface and the changing climate in the Sahel region of west central Africa. The Sahel is a semi-arid grass/shrub region, where localized overuse by man is causing damage to the fragile land surface. They compare AVHRR imagery obtained from the 1980-1984 rainy seasons to above-ground phytomass clippings, visual estimates and hand-held radiometer data at between 42 and 112 ground locations.

At each location, six to ten 1 m^2 areas were sampled. A good correlation (r=.80) was found between the yearly integrated AVHRR data and the end of season above-ground dry phytomass for the clipped samples. The data also show the applicability of the AVHRR system to the detection of ephimeral plant growth in ecosystems where woody species comprise less than 10% of the canopy - thereby indirectly monitoring the accuracy of highly variable rainfall. Primary production depends mainly on the available moisture, then on edaphic factors; however, because of the pastoral nature of the inhabitants, the primary production of grasses (and to a lesser extent the sparse woody plants) are directly linked to the density of the inhabitants.

Justice et al. (1985) used AVHRR imagery to monitor vegetative seasonal dynamics. Remotely sensed data were used to estimate the temporal vegetative dynamics in ecosystems ranging from rain forest to coastal deserts across Central and South America. Temporal seasonal dynamics of agricultural and non-agricultural locations in Asia were studied. The authors draw quantitative relationships between the integrated NDVI and rainfall in Indian forests; although the authors do not attempt statistical analysis of the data, average monthly rainfall is noted to be proportional to actual monthly-integrated NDVI, with NDVI peak months occurring after the rainfall peak months.

Norwine and Greegor (1983) classified vegetation across an east to west climatic gradient in Texas. The paper is particularly

interesting in that it applies a measure of moisture availability called the Hydrologic Factor (HF), which is sensitive to the physiological conditions important to the plant, in place of raw rainfall. The authors found a good correlation between the HF index and measured NDVI values (r=.80). The authors introduce a multivariate index, the product of the NDVI and HF indices, and apply this vegetation/climate factor to the analysis and differentiation of the phytomass in Texas. The authors foresee this relationship being used to remotely monitor key biogeographical processes and the dynamics of plant zone boundries.

2. DATA

The data set for this study consists of monthly integrated NDVI data and monthly total rainfall for the seventy-eight stations shown in figure 2.1. Effective rainfall, the difference between monthly rainfall and monthly potential evapotranspiration, was calculated for each of the locations.

The NDVI data was remotely sensed through the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA-8 and NOAA-9 Meteorological Satellites. Although higher resolution AVHRR imagery is available, the low-resolution Global Area Coverage (GAC) imagery was used, giving a pixel size with nominal dimensions of 4 km on a side. Dr. C.J. Tucker of the NASA Global Space Flight Center (GSFC) processed the NDVI data, and provided the processed NDVI data for the pixel closest to each of the seventy-eight stations. He also provided a mosaic of eight pixels surrounding the first pixel-giving a combined pixel with nominal dimensions of 12 km on a side (144 km^2 area covered). The data were provided on tape, in the form of monthly integrated NDVI for the period November 1982 to October 1985; and were manipulated further on the Florida State University Department of Meteorology Harris 800 minicomputer.

During processing at NASA/GSFC, a simple but effective filter was applied to the data to simultaneously reduce the detrimental effects

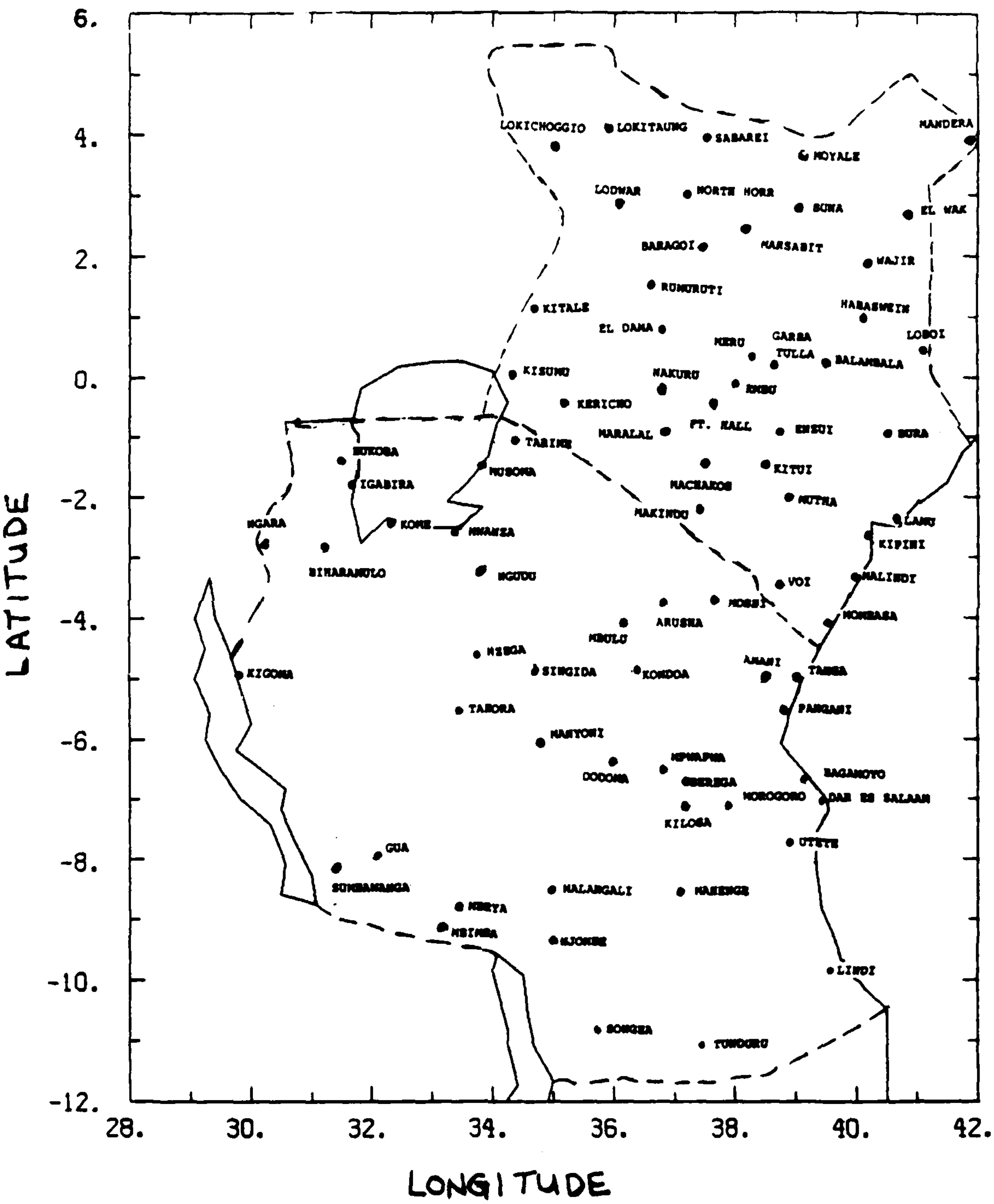


Figure 2.1. Location of stations used in this study.

of cloud cover, variable sun angle, atmospheric aerosols and variable atmospheric path length (Tucker, 1985a). A maximum-brightness filter was applied. Briefly, each pixel was imaged and recorded about every other day. Images were combined into 10-day composites. The brightest 10-day composited image was used to represent the monthly NDVI for the pixel.

As discussed previously, the rainfall in East Africa is highly variable in space, due to the generally unorganized character of convective precipitation (Nieuwolt, 1979). The high spatial variability would suggest the use of the 4km x 4km pixel NDVI data. However, man has a very large effect on the land surface surrounding the rainfall station, since rainfall measurement sites are generally in the most populated portion of villages. To most effectively average out the influence of structures and roads, grazing, burning, agriculture, and surface water sources on NDVI, data from the composited 12km x 12km pixel should be used. Data from the larger 12 x 12 composited pixels were used, as it is felt that the land surface anomalies introduced more error into the problem than did the decreased representativeness of the rainfall.

The rainfall data set was provided by Dr. Sharon Nicholson. The data set is a compilation from many sources - including WMO records and face-to-face contact with personnel at the Kenyan and Tanzanian Meteorological Services - and is a subset of a larger African rainfall climatology set as described in Nicholson (1986). The rainfall data are in the form of monthly rainfall totals. Periods of record

Table 2.1. Means and standard deviations of rainfall data and Potential Evapotranspiration. (Coefficient of Variation [CV] is described in the text, page 6).

STATION NAME	AVERAGE RAIN(mm)	STD DEV	CV	PERIOD OF RECORD(Yr)	AVERAGE PET(mm)
KENYA					
Balambala	259	163	.629	25	2212
Baragoi	490	103	.210	23	938
Buna	175	41	.234	4	1524
Bura	307	96	.313	4	2477
El Dama	1041	351	.337	47	885
El Wak	226	84	.372	14	1874
Embu	1078	285	.264	55	938
Enzui	467	267	.572	20	1411
Ft. Hall	1182	347	.294	55	901
Garba Tulla	256	197	.769	11	1690
Habaswein	164	81	.494	4	2054
Kericho	1864	292	.157	55	780
Kipini	867	406	.468	52	1495
Kisumu	1106	216	.195	55	1133
Kitale	1168	263	.225	55	809
Kitui	1034	378	.366	55	988
Lamu	931	290	.315	55	1502
Loboi	342	77	.225	4	2473
Lodwar	174	106	.609	55	2379
Lokichoggio	431	214	.497	12	1172
Lokitaung	390	191	.489	54	1706
Machakos	903	264	.292	55	858
Makindu	543	216	.398	55	1086
Malindi	1039	343	.330	55	1602
Mandera	222	118	.532	44	1920
Maralal	558	144	.258	25	733
Marsabit	823	312	.374	55	884
Meru	1339	402	.300	55	890
Mombasa	1192	314	.263	55	1676
Moyale	712	226	.317	55	1053
Mutha Dispensary	500	189	.378	12	1465
Nakuru	850	165	.194	55	805
North Horr	120	101	.842	4	1484
Rumuruti	607	204	.336	54	790
Sabarei	217	103	.475	7	1358
Voi	537	184	.343	55	1357
Wajir	288	171	.594	55	1928

STATION NAME	AVERAGE RAIN(mm)	STD DEV	CV	PERIOD OF RECORD(Yr)	AVERAGE PET(mm)
TANZANIA					
Amani	1894	354	.187	55	947
Arusha	1092	360	.329	55	872
Bagamoyo	1062	257	.242	55	1506
Berega	758	241	.318	55	1347
Biharamulo	919	244	.266	55	968
Bukoba	2076	268	.129	55	969
Dar Es Salaam	1038	244	.236	55	1507
Dodoma	557	145	.260	55	1101
Gua	935	307	.328	36	1014
Igabira	1142	358	.314	55	954
Kigoma	915	273	.298	55	1174
Kilosa	1033	226	.219	55	1259
Kome	972	454	.467	43	1097
Kondoa	626	217	.347	55	984
Lindi	903	271	.300	55	1560
Madibira	601	286	.476	55	1112
Mahenge	1958	458	.234	55	1142
Malangali	683	310	.454	54	661
Manyoni	613	177	.289	55	1171
Mbeya	885	196	.221	55	792
Mbimba	1681	533	.317	40	879
Mbulu	833	224	.269	55	806
Morogoro	865	267	.309	55	1294
Moshi	899	306	.340	55	1184
Mpwapwa	709	186	.262	55	946
Musoma	819	220	.269	55	1131
Mwanza	1046	244	.233	55	1097
Ngara	1015	165	.162	55	874
Nqudu	803	254	.316	55	1061
Njombe	1092	237	.217	55	747
Nzega	795	161	.203	54	1152
Pangani	1238	367	.296	55	1573
Shanwa	774	268	.346	55	1020
Singida	673	169	.251	55	1017
Songea	1147	215	.187	55	971
Sumbawanga	774	371	.479	55	799
Tabora	866	196	.226	55	1122
Tarime	1305	504	.386	55	961
Tunduru	1010	284	.281	55	1194
Utete	862	272	.316	55	1622
Zanzibar	1434	409	.285	55	1529

for most locations outside of the arid portion of northern Kenya are at least 50 years. Precipitation means and standard deviations for the long-term period (e.g., 1930-1985) and the 1983-1985 study period are shown in table 2.1.

While this rainfall climatology set is probably the most comprehensive available, total monthly rainfall values by themselves are of limited value in explaining plant growth and development. Data such as rainfall duration, frequency, and intensity were not available and had to be ignored during this study. The ideal study would consider these factors carefully.

Soil characteristics are important in determining the range and distribution of plant types in East Africa. The soil types of the region have been mapped in detail (Director of Agriculture, 1955), but for the purposes of this study, regional soils will be considered to be similar enough in water holding characteristics to be assumed equal. Exceptions will be presented on a station-by-station basis to explain observed deviations in NDVI.

Stations are grouped into categories by vegetation zone. An African vegetative mapping compiled by White (1983) was chosen because of its recency, ease of application to vegetation types worldwide, and the specific sub-grouping of the major vegetation types. The vegetation zones are distinguished in terms of the physical characteristics of the vegetation, not in terms of climatic characteristics (like the Köppen Scheme). Figure 2.2 shows the location of the vegetative zones.

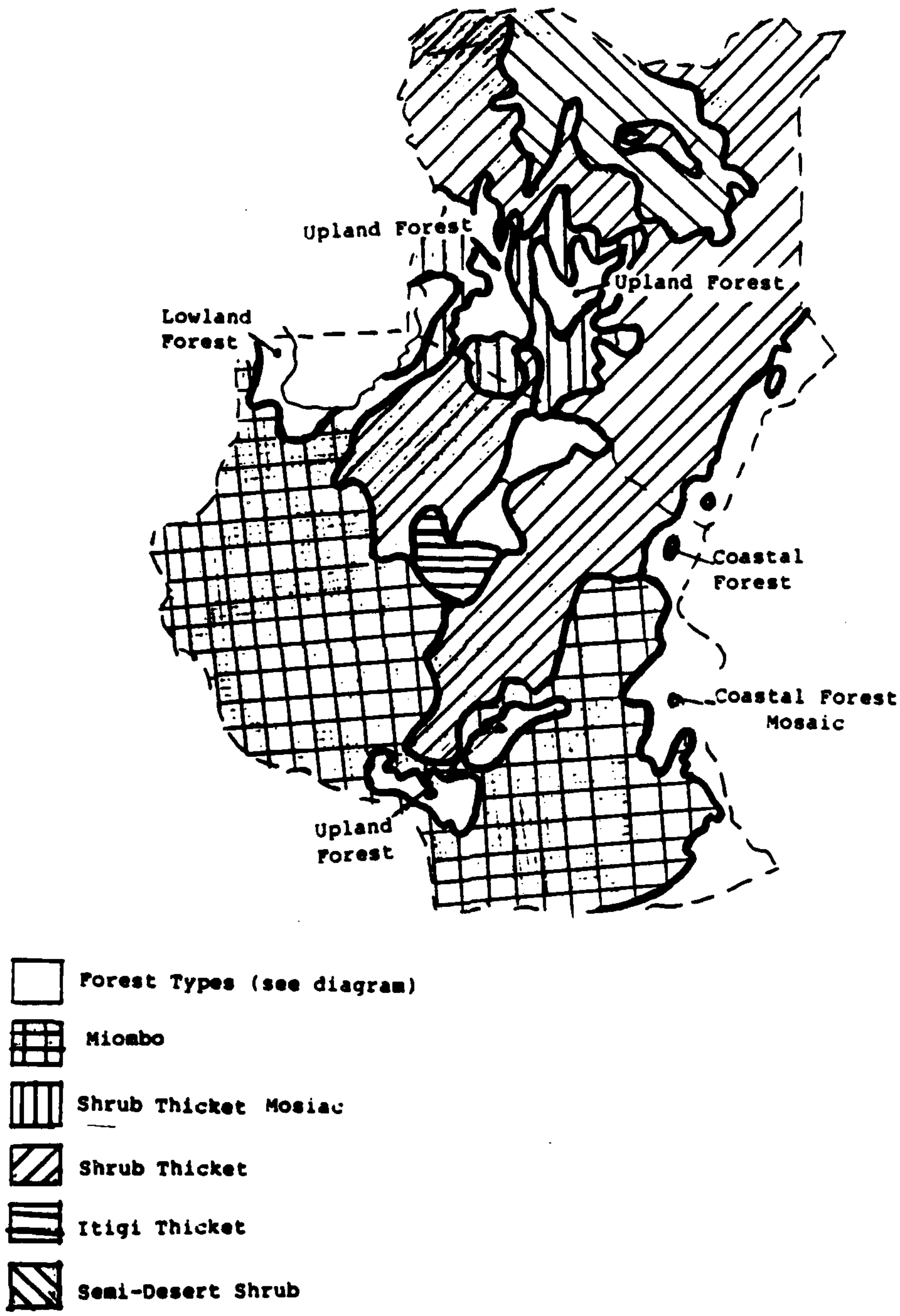


Figure 2.2. UNESCO vegetative mapping of East Africa (from White, 1983).

Effective rainfall - the difference between rainfall and water loss through potential values of evaporation and transpiration (potential evapotranspiration [PET]) - provides a better estimate of the water available for plant use than does rainfall alone. Much effort was spent during this study to determine and implement a suitable PET estimation model, so that monthly effective rainfall could be determined for all stations during the test period. Of the many models available, the lack of available data prescribed the use of the Thornthwaite method for estimating PET (Palmer and Havens, 1958). The data available for input to this model (30 year averages of monthly station temperature) provided only long-term average PET: so monthly effective rainfall values obtained by the difference between actual monthly rainfall and the climatological average of PET for the month do not take into consideration the sometimes large year-to-year variation of monthly PET. Because of this data constraint, rainfall alone was used as the moisture variable in correlations with NDVI on a monthly basis; while on the yearly and three-yearly time scales, both effective rainfall and rainfall are used.

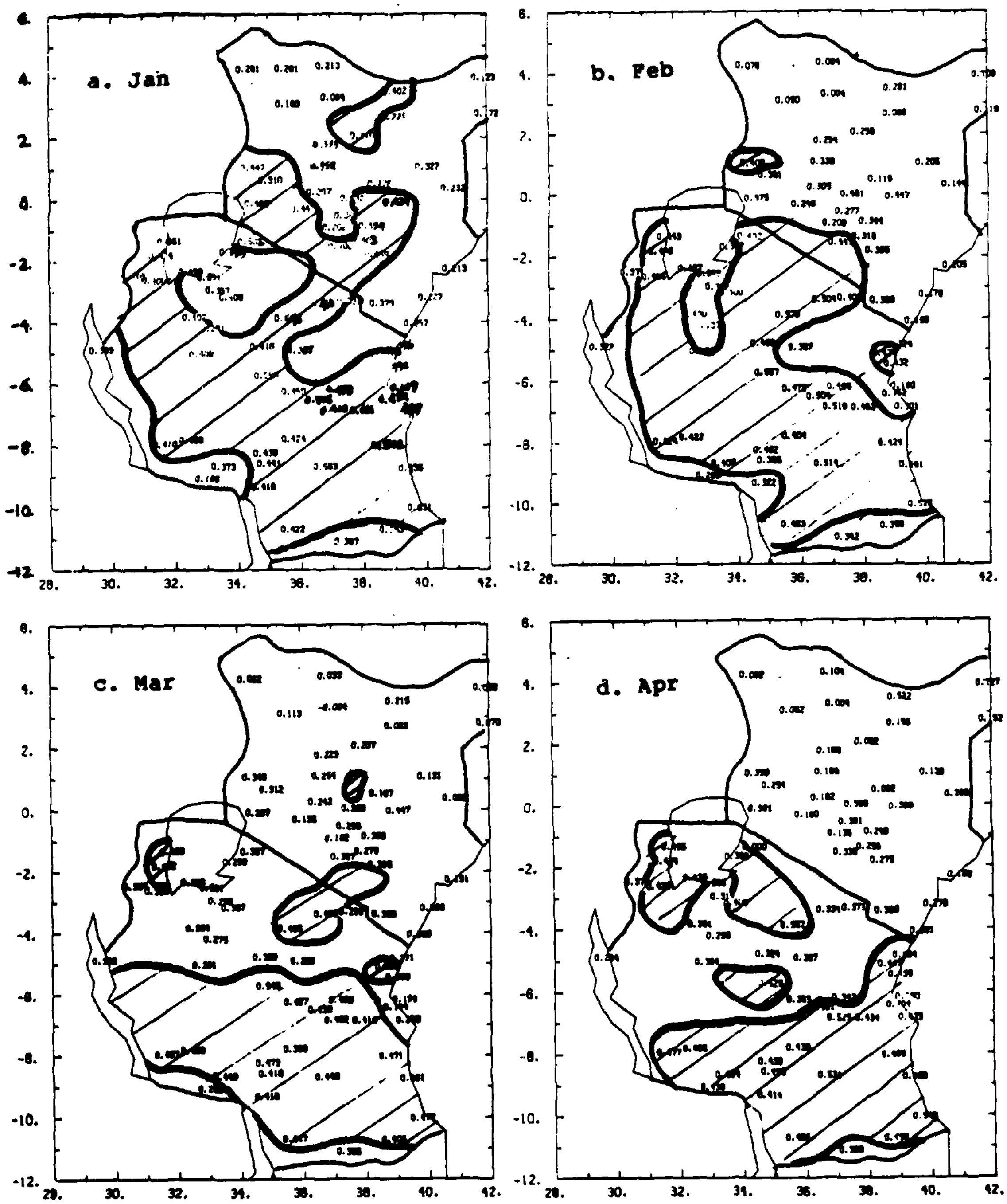
3. RESULTS AND DISCUSSION

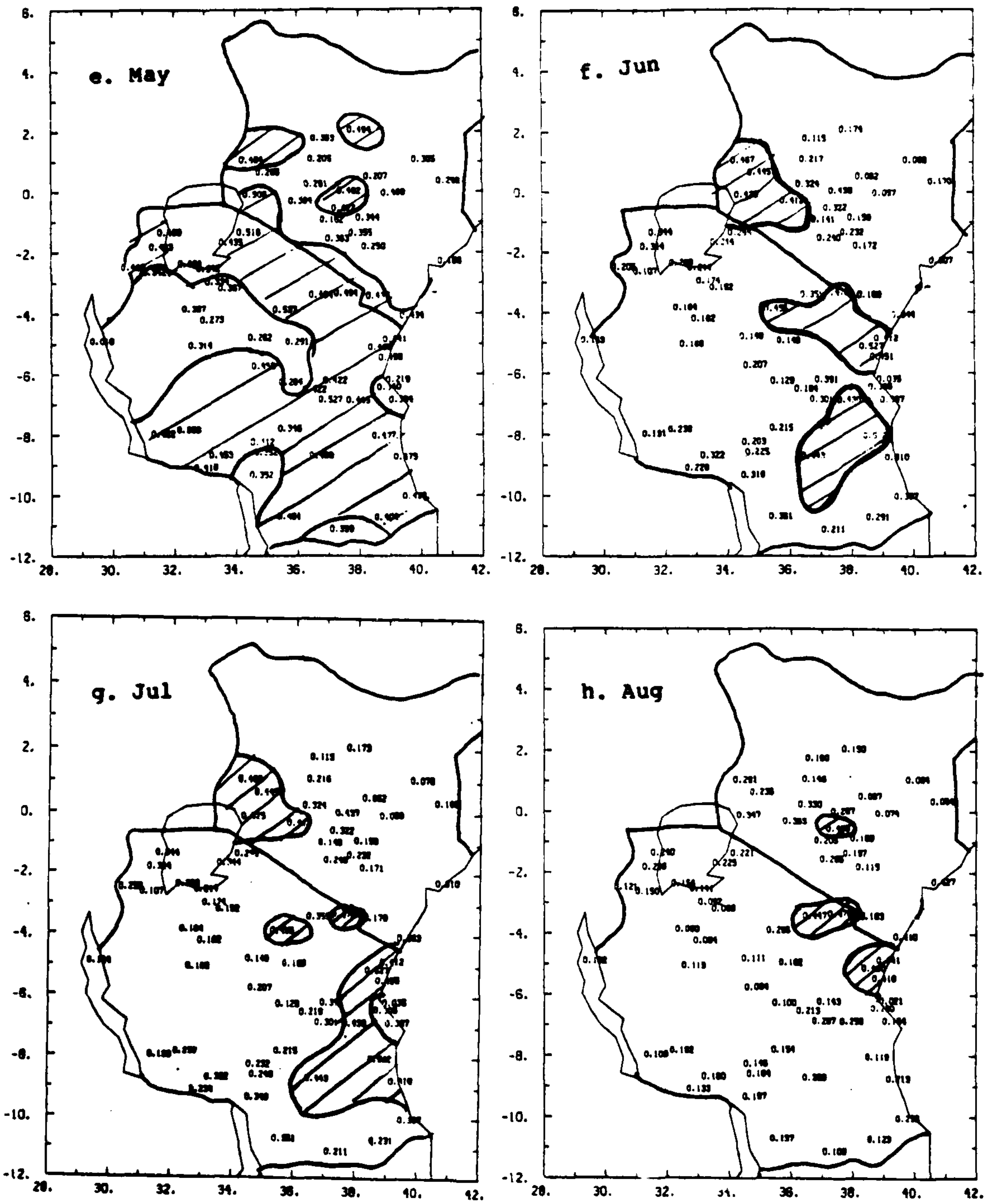
The relationships between the greenness of the land surface as measured from space, and observed rainfall are concise and quantifiable. This section will present these relationships with respect to spatial and temporal patterns, and will attempt to measure the correlation between monthly-integreted NDVI and monthly rainfall and the time lags involved between the rainfall event and the NDVI response. In the course of these comparisons, NDVI behavior both in time and in space in East Africa is described. Two vegetative mapping procedures will be attempted.

3.1 DESCRIPTION OF NDVI PATTERNS

Discussion of the results begins with the description of spatial and temporal patterns of NDVI in Eastern Africa. Figure 3.1.1 shows a month-by-month sequence of station NDVI from January 1983 through December 1983 in East Africa. The shaded area on each map encloses the area with highest monthly NDVI value (i.e.: NDVI >.40). With a few exceptions, high NDVI values do not persist over regions, but "move" in response to the seasonal movement of rainfall associated with ITCZ migration. Persistently high NDVI values are found at the western shore of Lake Victoria, and the Kenyan and Tanzanian highlands. Lowest NDVI values are a relatively fixed phenomenon, found in the most arid portions of semi-desert northern Kenya

Figure 3.1.1. Monthly NDVI from January 1983(a) to December 1983(l). Shaded area indicates monthly NDVI greater than .40.




e. May
f. Jun
g. Jul
h. Aug
6.
4.
2.
0.
-2.
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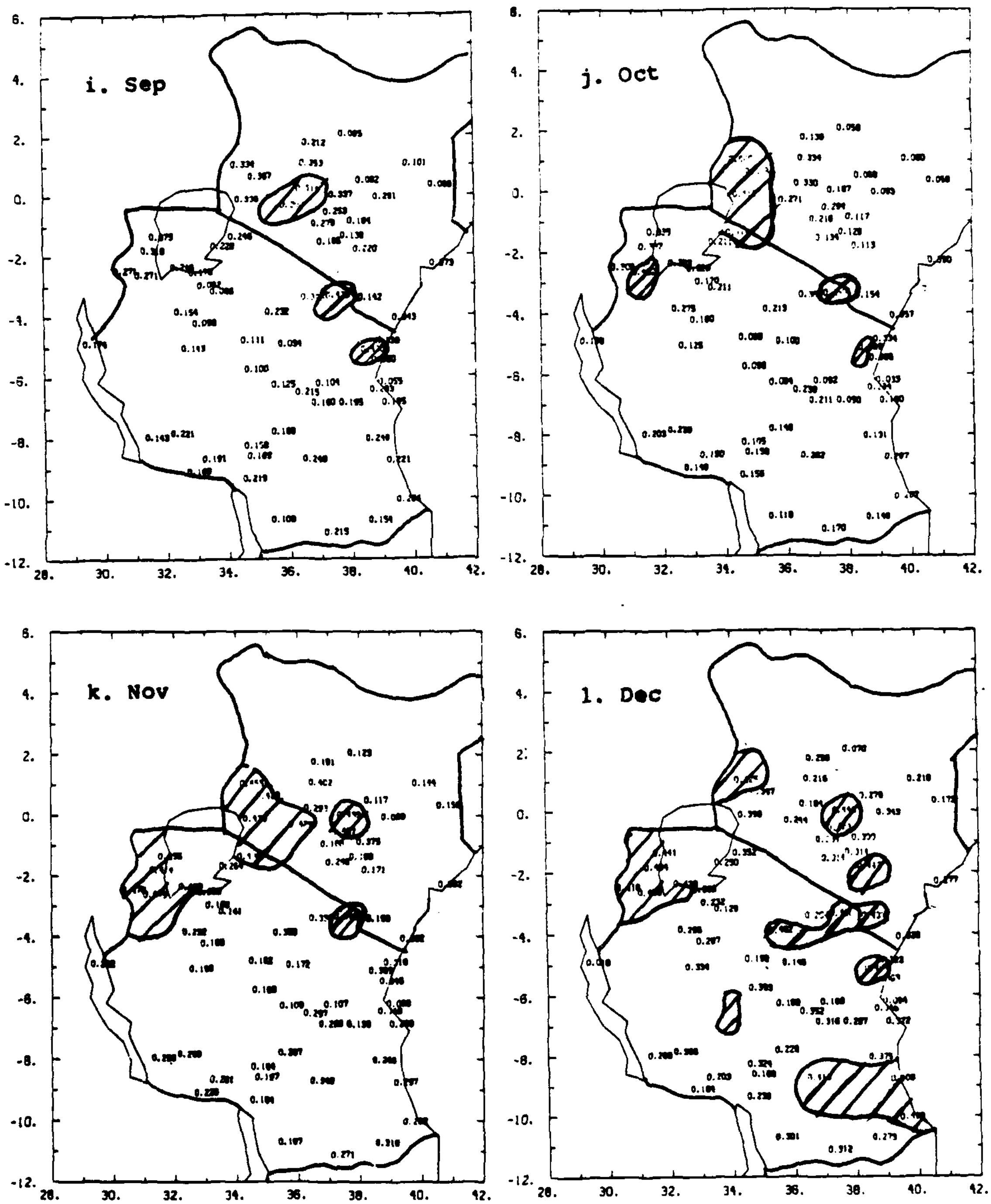
42.


i. Sep
j. Oct
k. Nov
l. Dec

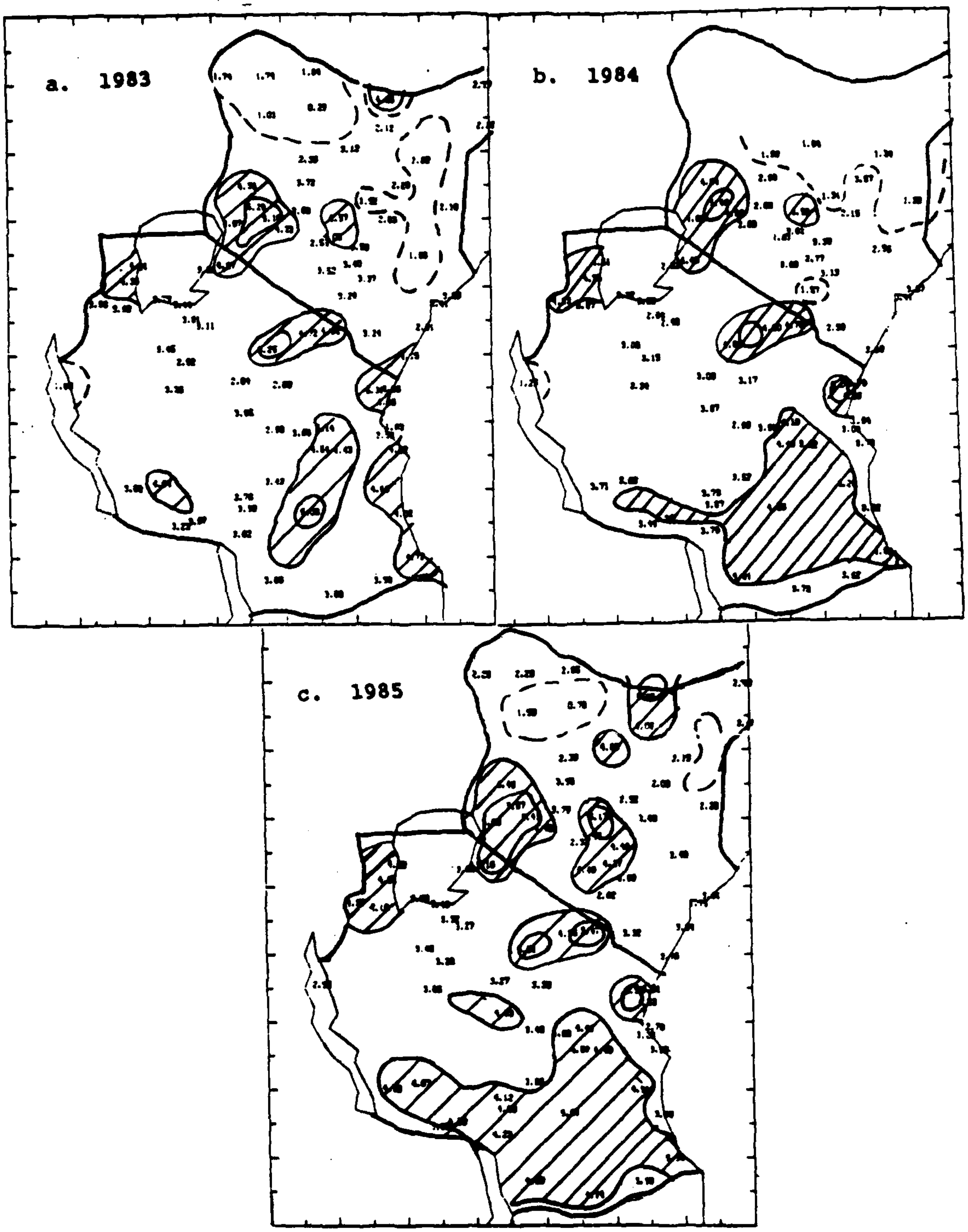
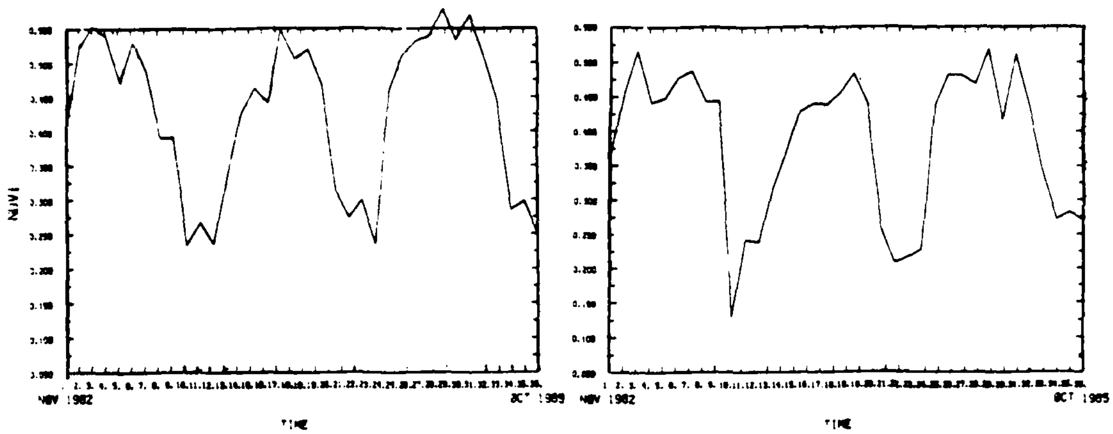


Figure 3.1.2. Yearly-integrated NDVI. Stippled area indicates maximum NDVI values. (NDVI >4.0), dashed line encloses NDVI values < 2.0.

throughout the year. The Miombo woodlands of southern Tanzania experience large seasonal variation in monthly NDVI, as would be expected because the deciduous vegetation, that comprises much of the phytomass, sheds leaves during the long dry season.

Year-to-year patterns of yearly integrated NDVI are shown in Figure 3.1.2. On a yearly averaged basis, highest NDVI values (yearly-integrated NDVI >.4.0) are again found over the Southern Tanzanian highlands, and the region to the west of Lake Victoria. Somewhat surprising is the large year-to-year variation in the magnitudes of the NDVI values at stations in the greenest locations. Since these stations represent the closest thing to rain forests found in East Africa, one would anticipate persistently large NDVI values indicative of a tropical jungle. As will be discussed later, the short dry periods found in even the wettest areas of the region have an effect on the greenness of the plant canopy.

The time series behavior of NDVI for selected stations will be briefly presented. Figure 3.1.3a compares the time series plot of NDVI for a station in the coastal forest zone to that of a station in the Miombo zone. The size of the NDVI difference between wet and dry seasons is smaller at the coastal forest station. Although the 3-year NDVI means are similar, the temporal behavior of the two series are to some extent distinguishable. Visible in the time series of the example from the Miombo woodland zone is the small "green" peak in the middle of the NDVI time series trough, characteristic of the deciduous Miombo zone of Tanzania. This small



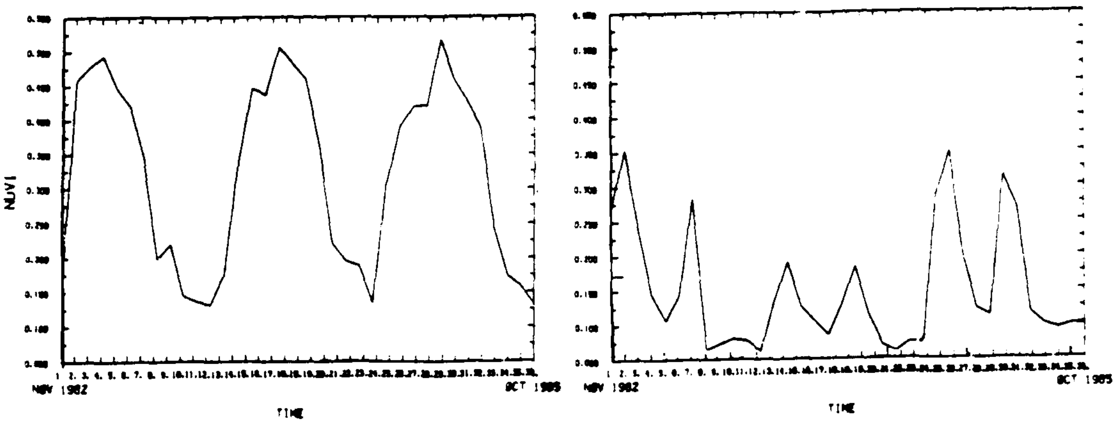
Miombo Woodland zone

Coastal forest zone.

Figure 3.1.3 a Comparison of NDVI time series from November 1982 to October 1985 at two stations.

maximum NDVI peak occurring during the driest part of the year is probably due to the brilliant blossoming and appearance of new shoots on plants in the genus Brachystegia, the dominant plant found in the Miombo woodland (Lind and Morrison, 1974). Most deciduous plants begin to produce leaves and blossoms after the start of the rains, the Brachystegia is unique in that it blooms 4-6 weeks before the start of the rains.

Also interesting is the contrast between stations within the same plant zone, but in different rainfall regimes. Figure 3.1.3b compares Mpwapwa - located in Central Tanzania, under the influence



Mpwapwa

Wajir

Figure 3.1.3 b Comparison of NDVI time series from November 1982 to October 1985 at two stations.

of unimodal rainfall distribution; and Wajir, a station in northern Kenya and a under a bimodal rainfall regime. Although both locations are grouped into the same plant zone (shrub-thicket), the NDVI curves are very different. Most obvious is the larger magnitude of the NDVI peaks; the lack of change in the magnitude of the peak from year-to-year at Mpwapwa (a reflection of the wetter conditions); and the seasonal responses of NDVI to the rainfall regimes of the stations (two peaks per year at Wajir with two rainy seasons compared to one at Mpwapwa with a unimodal rainfall seasonality).

3.2 SPATIAL RELATIONSHIPS BETWEEN NDVI AND RAINFALL

On a year-to-year basis, areas with highest annual rainfall and effective rainfall correlate well with areas of maximum yearly-integrated NDVI. Figures 3.2.1a through 3.2.1c illustrate the spatial correlation among annual rainfall, effective rainfall and integrated NDVI for the 1983-1985 period. Shaded areas indicate the largest values, and dashed lines enclose the areas of minimum values, these values are: NDVI > 4.0 and <2.0; rain >1000mm and <500mm; and effective rain >0 and <-1500mm, respectively. The persistently low NDVI values discussed earlier occur at stations with lowest annual rain and effective rain values.

To further illustrate spatial relationships, the three-year averages of rain, effective rain and integrated NDVI, were plotted along four land surface transects. The first two transects were selected to show the meridional and zonal relationships between moisture and greenness, and were placed to include as many stations as possible. Both transects span varied topography and plant zones. Transect 1, (figure 3.2.2a) drawn north to south across the interior of East Africa, shows the very clear correlation: where rain is high, NDVI is high. While both effective rain and rain are correlated with NDVI, the effective rainfall seems to correlate better. The problems discussed earlier in using effective rain derived from average monthly PET become less important when using a three-year average, because variation decreases as averaging time increases.

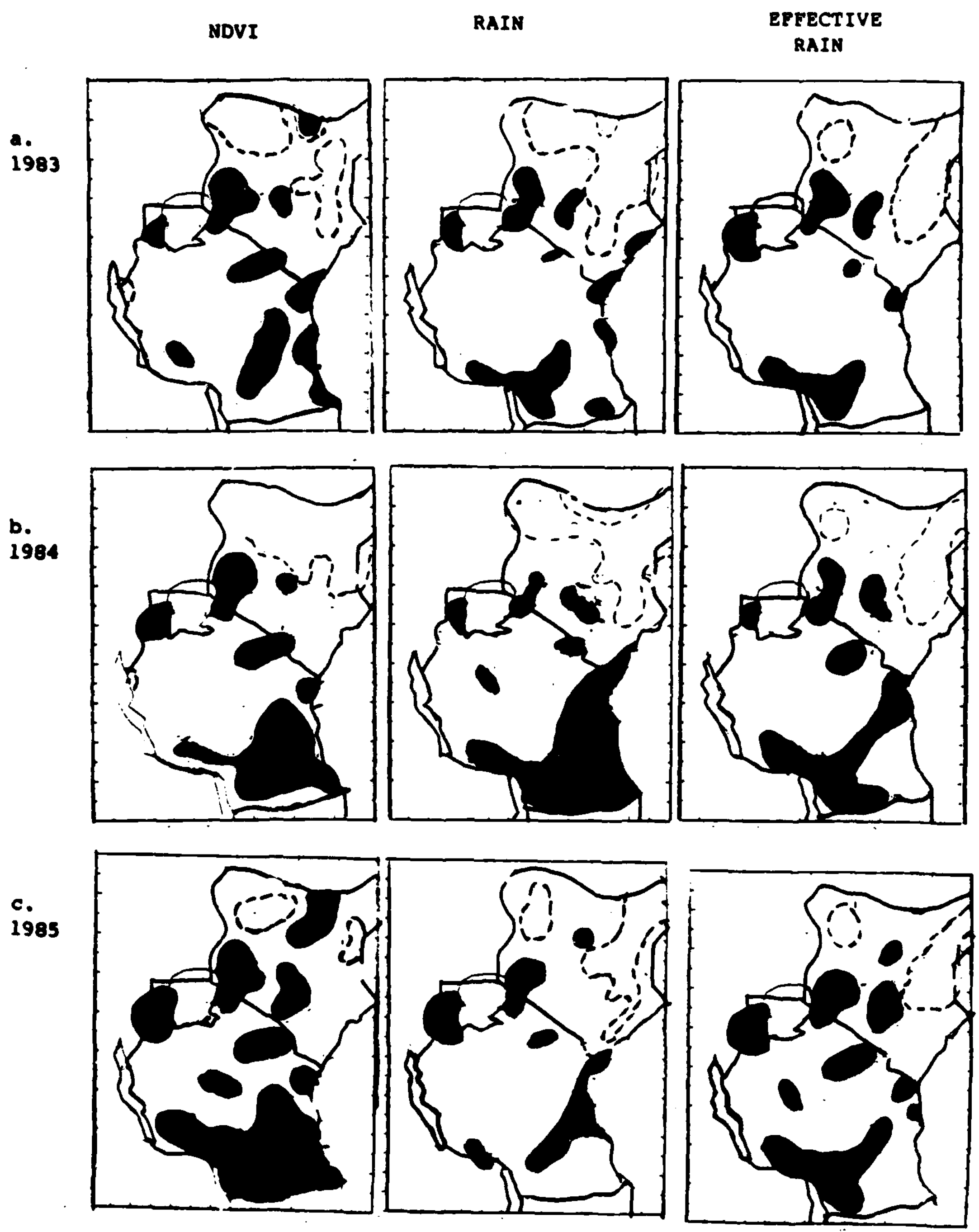


Figure 3.2.1. Annually-integrated NDVI, rainfall and effective rainfall for East Africa Shaded areas indicate maximum values (NDVI >4.0, rain >1000mm, effective rain >0mm),dashed lines enclose areas of minimum values (NDVI <2.0, rain< 500mm, effective rain <-1500mm).

The second transect, figure 3.2.2b, extends eastward from near Lake Victoria to the wet upland region through the foothills and arid interior, to the narrow high rainfall band near the coast of Kenya. While the relationship between NDVI and the moisture indices at all stations is less clear than in the previous transect, the same

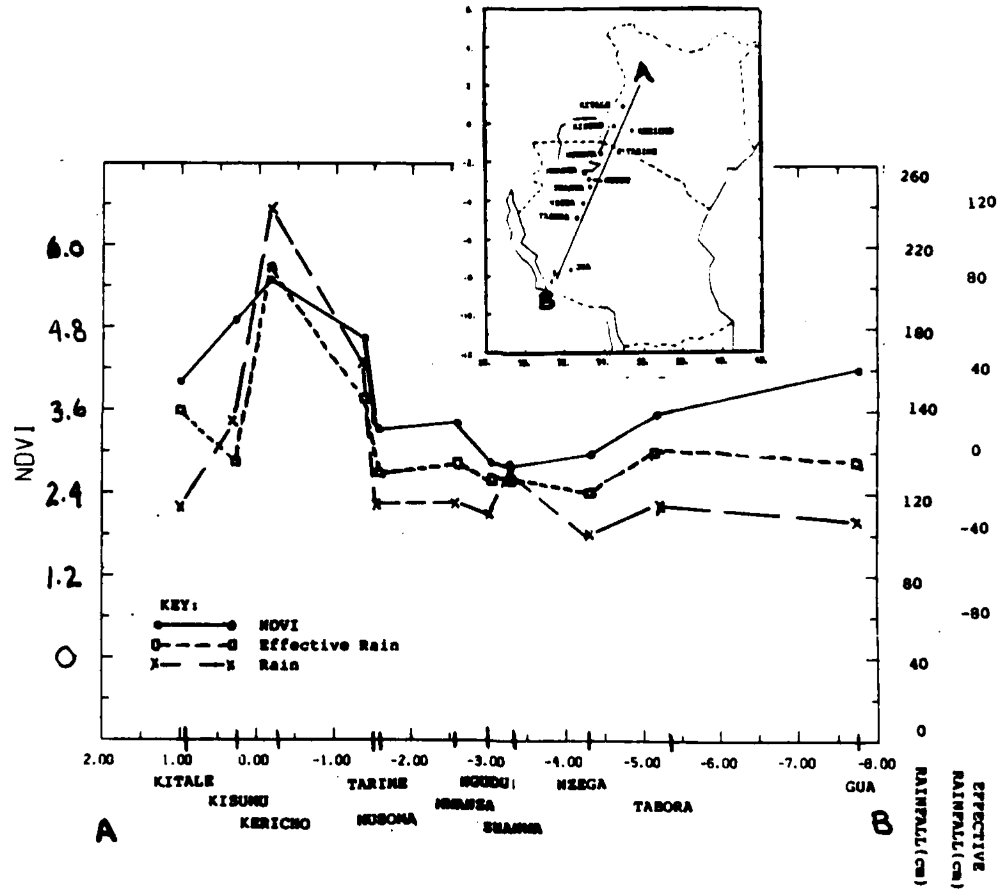


Figure 3.2.2a. Transect 1. Surface transect of the three-year average of rainfall, effective rainfall and NDVI. Inset shows the transect location.

general agreement is found. Note the relatively large NDVI values at the stations of Enzui and Mutha, where rainfall and effective rain-

fall are low. Although NDVI should decrease with decreasing moisture, the large NDVI values are probably a result of farming around these stations.

Two other transects were chosen to illustrate the gradients of rainfall and NDVI within single plant zones. The first of these transects is located in the largest plant zone, the shrub-thicket zone (figure 3.2.3a). The physical characteristics of the plants are

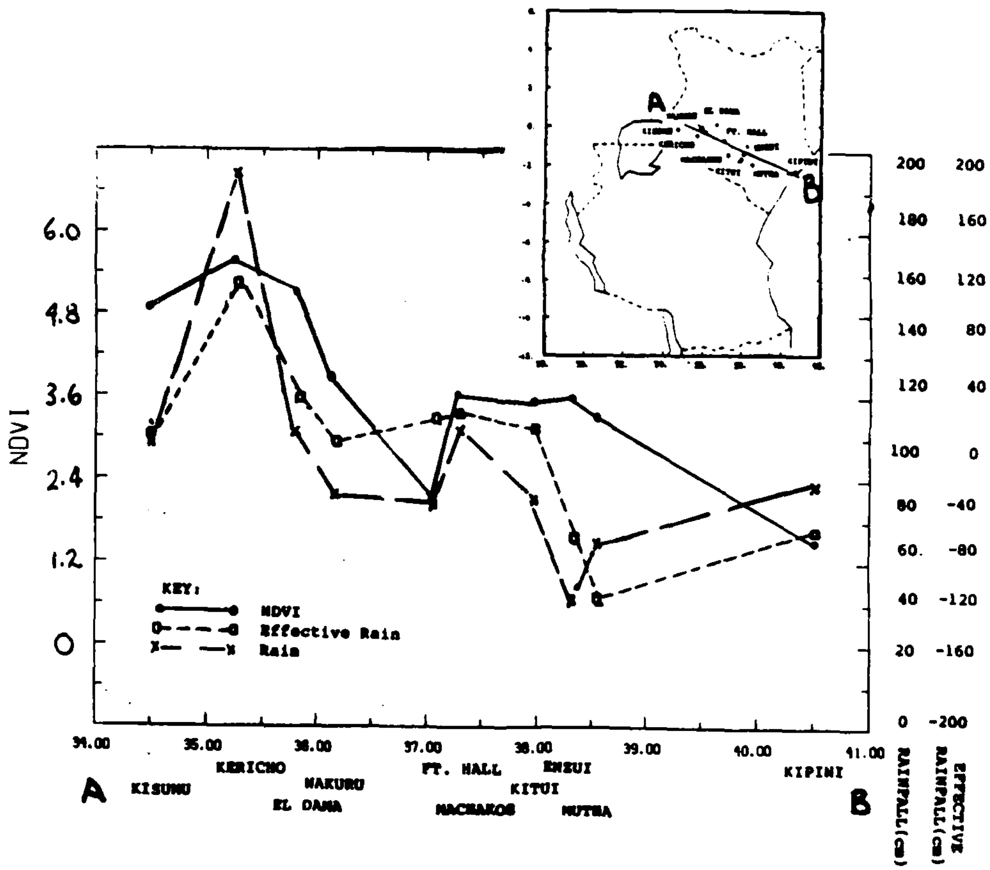


Figure 3.2.2b. Transect 2. Surface transect of the three-year average of rainfall, effective rainfall and NDVI. Inset shows the transect location.

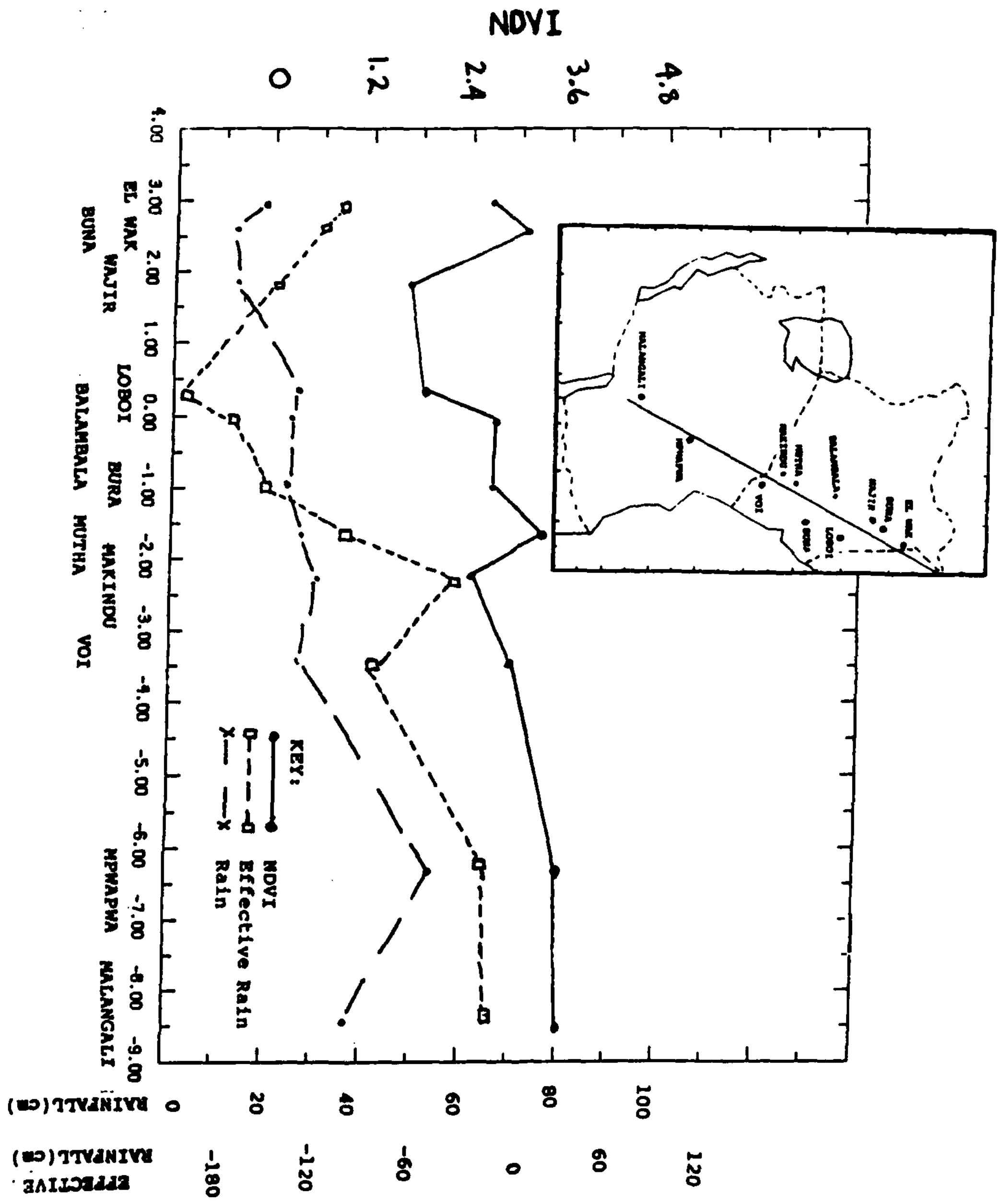


Figure 3.2.3a. Transect 3. Surface transect of the three-year average of rainfall, effective rainfall and NDVI. Inset shows the transect location.

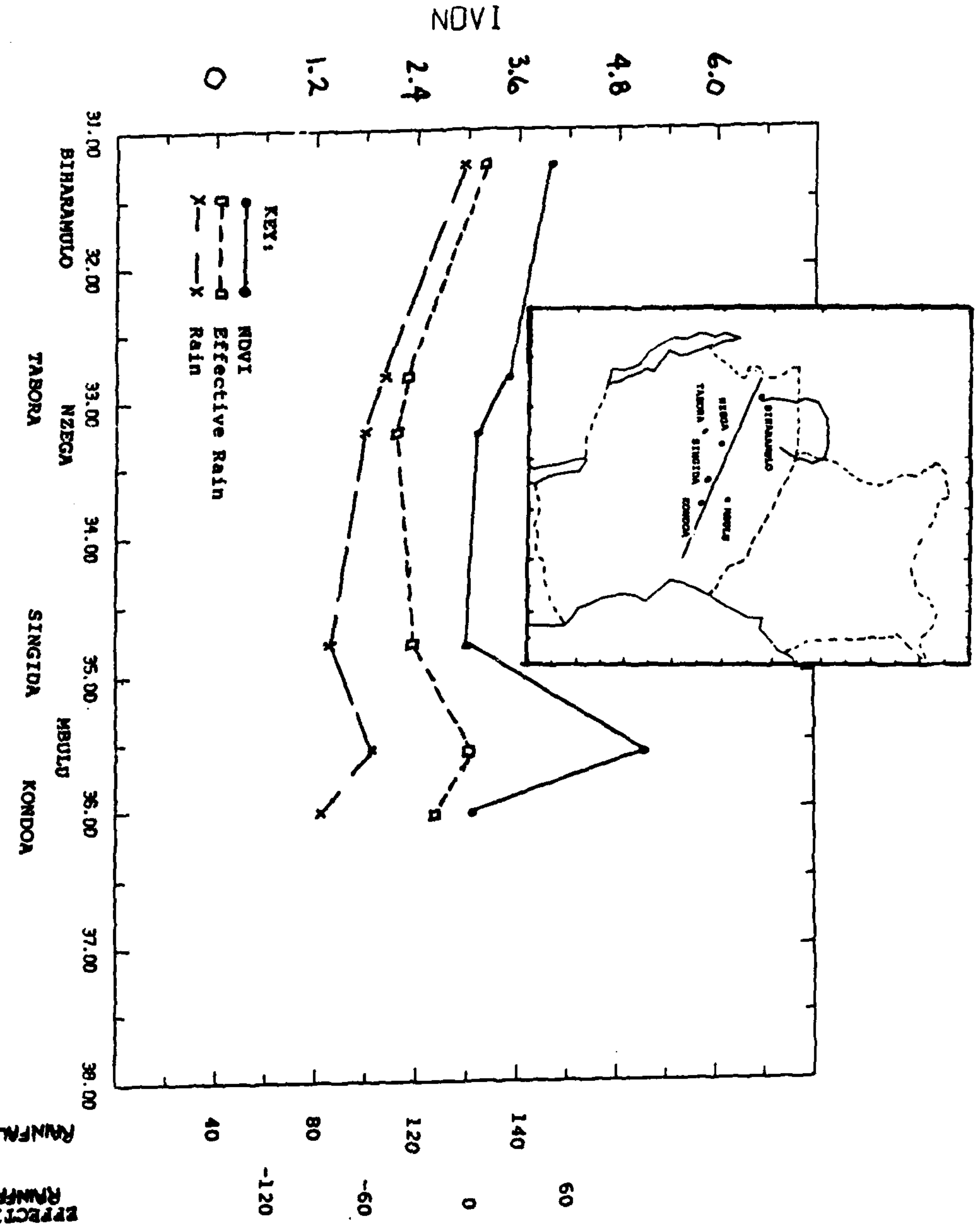


Figure 3.2.3b. Transect 4. Surface transect of the three-year average of rainfall, effective rainfall and NDVI. Inset shows the transect location.

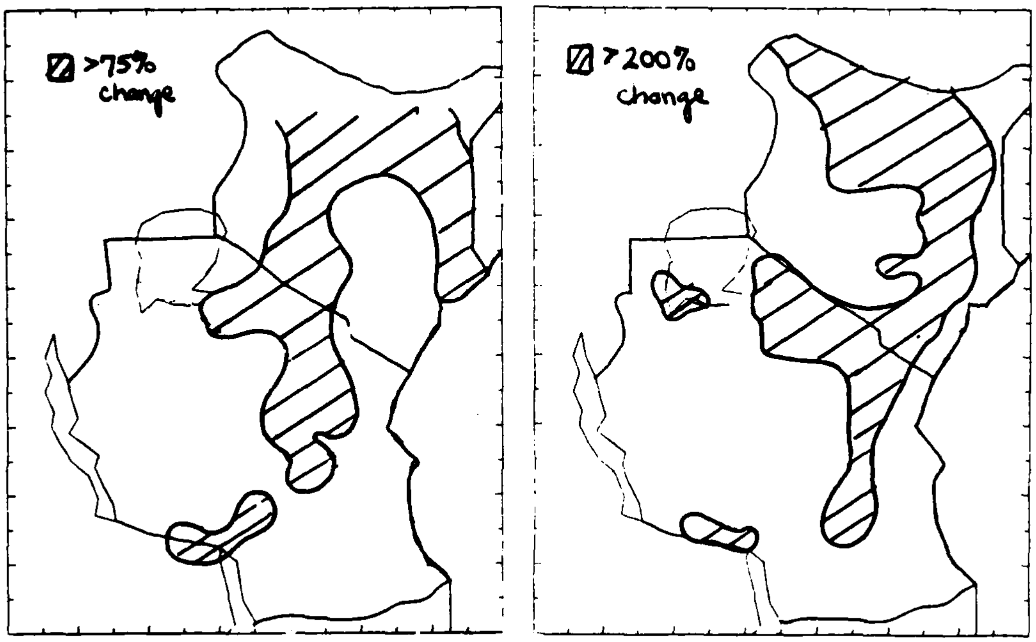
theoretically the same throughout the entirety of the zone, and rainfall and evapotranspiration gradients are much more gradual than those found in other parts of Eastern Africa. The relationship between rainfall and NDVI is especially apparent.

The last transect (figure 3.2.3.b) illustrates the relationship between stations located in the Miombo woodlands of northern Tanzania. Again, the relationship between NDVI and moisture is clear for a transect located within a single vegetative zone. Notice, however, that the rainfall, effective rainfall and NDVI averages are not perfectly synchronized. Higher rainfall or effective rainfall does not always create a higher NDVI value. This could be the result of one of the many environmental factors contributing to plant growth (temperature, soils, the nature of rainfall, or the influence of human habitation) that vary from place to place; or the plant types themselves.

3.3 TEMPORAL RELATIONSHIPS BETWEEN NDVI AND RAINFALL

It has been shown that yearly NDVI patterns correspond with rainfall patterns in terms of the locations of relative maximums and minimums. An example of the temporal link between rain and NDVI will be illustrated by comparing rainfall and NDVI differences between the abnormally dry December of 1983 and the wet December of 1984. Vegetation greenness should change little from one December to the next December, unless rainfall changes. The drier conditions in 1983 should result in low NDVI values, with the following year's wet conditions creating higher NDVI values.

The NDVI and three-month moving average of rainfall for each of the stations was differenced (1983 minus 1984), and a relative change was calculated ((1983-1984)/1984). The resulting data plots (figure 3.3.1) were obtained. The areas of the largest relative differences



a. NDVI relative differences. b. Rainfall relative differences.

Figure 3.3.1. Relative difference plots between December 1983 and December 1984.

of NDVI and rainfall (75% and 200%, respectively) are enclosed in the stippled areas on the maps. All stations that show a difference in rainfall (i.e., December 1983 drier than December 1984), also show a

difference in NDVI (i.e., December 1983 NDVI lower than December 1984 NDVI). Also apparent is the coincidence of the areas of the largest relative change (stippled area) and remaining areas of the smallest relative change in both the rainfall and NDVI difference plots. These areas do not exactly overlap, probably due to the physical characteristics of the soil, drought - dynamics of the vegetation, or by the varying nature of the rainfall.

To summarize the spatial and temporal relationships between rainfall and NDVI, spatiotemporal plots of monthly NDVI and three-month moving average of rainfall are presented for each of the surface transects described earlier. Figures 3.3.2 through 3.3.5 graphically represent the variation in time and space of NDVI and rainfall, and compare NDVI and rainfall patterns. The three-month moving average of rainfall, the average of the two previous months and the current month rain, is used in the place of the actual monthly rain (e.g., the rain value given for November 1982 is the average of September, October, and November 1982).

The two transects chosen for meridional and zonal purposes show how the seasonality and character of both rainfall and NDVI change from North to South (figure 3.3.2) and from West to East (figure 3.3.3) along the transects. Figure 3.3.2 clearly shows that both the rainfall and the NDVI seasonality becomes increasingly unimodal from North (left) to South (right), as the vegetation transitions from highland forest to woodland. Figure 3.3.3 shows the wetter than normal short rain of 1984 over the eastern highlands of Kenya, and

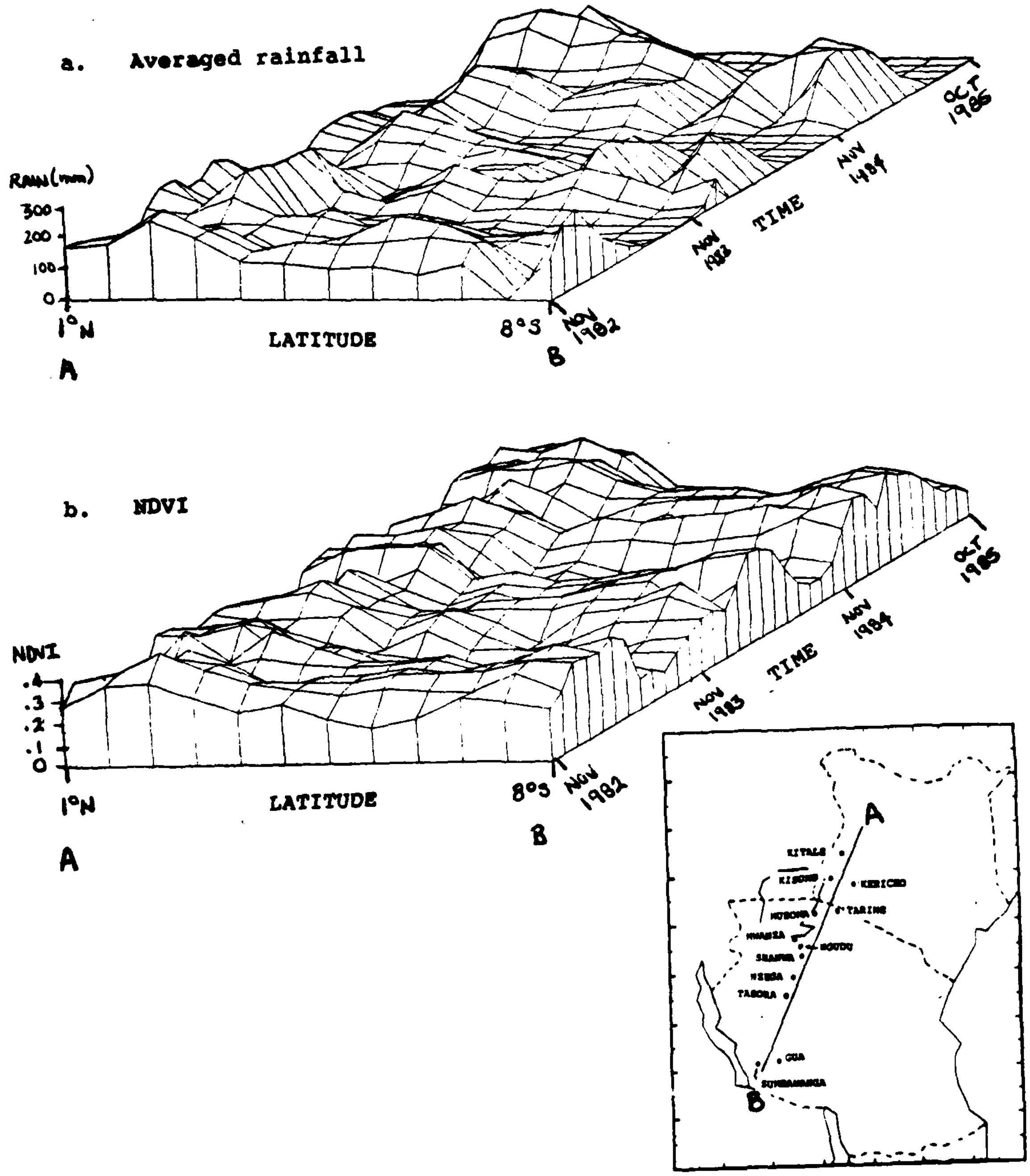


Figure 3.3.2. Spatiotemporal plot of monthly NDVI and three-month moving average of rainfall for transect 1 from November 1982 to October 1985.

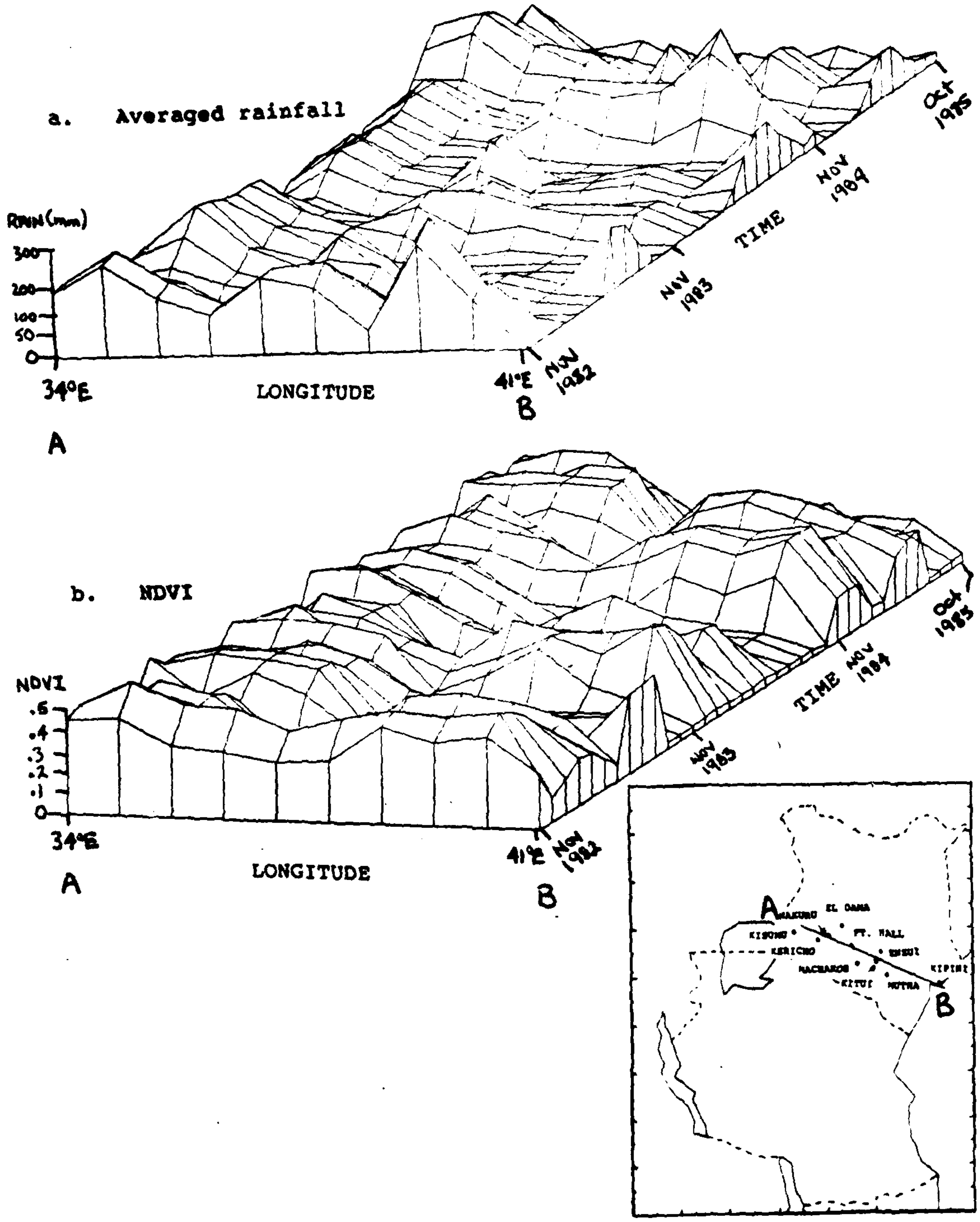


Figure 3.3.3. Spatiotemporal plot of monthly NDVI and three-month moving average of rainfall for transect 2 from November 1982 to October 1985.

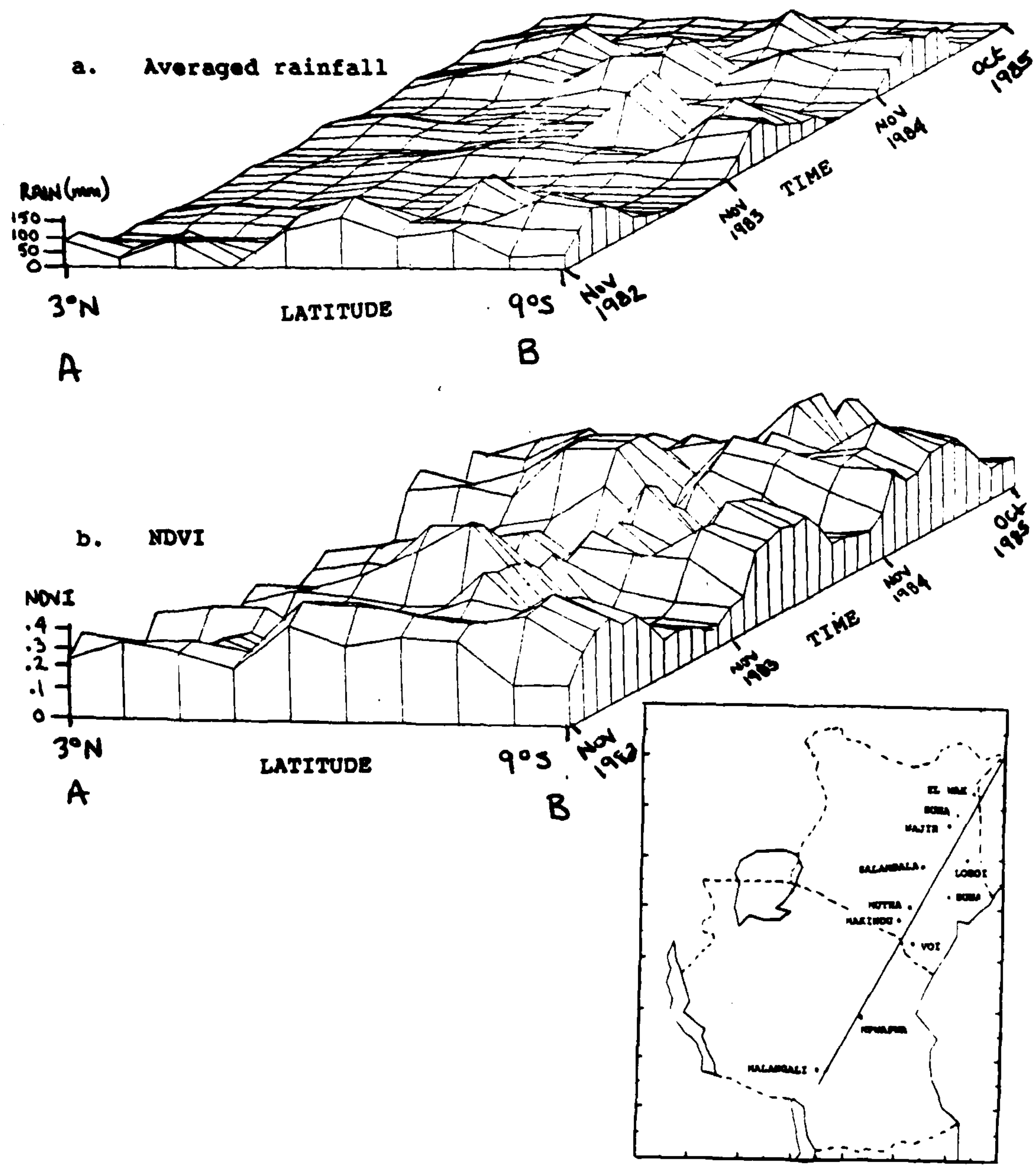


Figure 3.3.4. Spatiotemporal plot of monthly NDVI and three-month moving average of rainfall for transect 3 from November 1982 to October 1985.

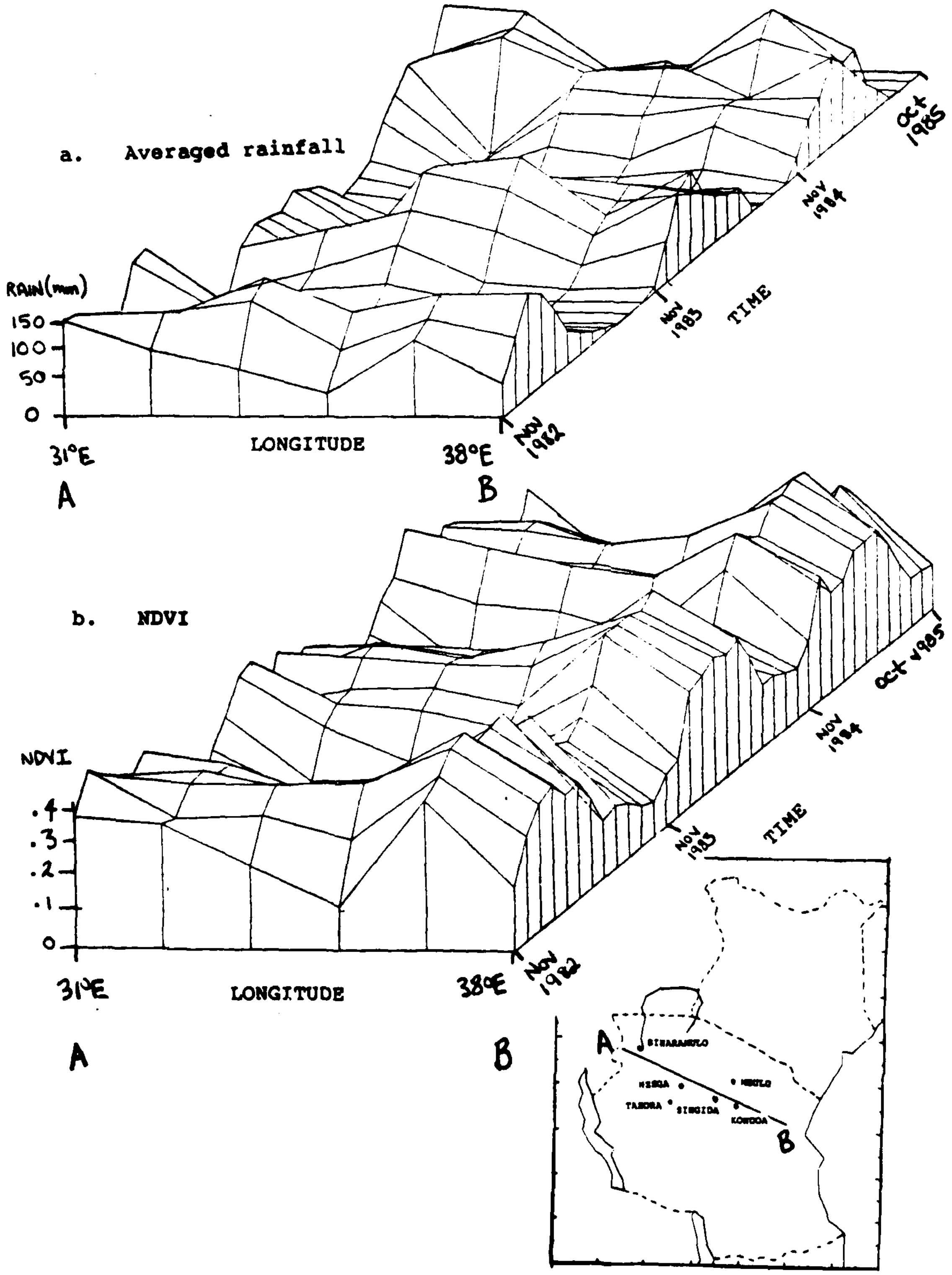


Figure 3.3.5. Spatiotemporal plot of monthly NDVI and three-month moving average of rainfall for transect 4 from November 1982 to October 1985.

the corresponding higher than normal NDVI response.

The two remaining figures (figure 3.3.4 and 3.3.5) show the more obvious relationship between NDVI and rainfall patterns at the two transects contained in a single plant zone. The variable seasonality of NDVI and rainfall is illustrated in the North to South transect across the shrub-thicket zone (figure 3.3.4). Although the physical characteristics of the vegetation are the same throughout the north to south transect, the seasonal behavior of the vegetatation varies along the transect: the NDVI shows no clear oscillations over the north parts of the transect, but over southern parts of the transect, the NDVI values exhibit large periodic oscillations. The seasonal NDVI response appears to be determined by the gradually changing rainfall seasonality from north to south along the transect. Figure 3.3.5, located in the Miombo Woodland zone of northern Tanzania, shows the similarity between the NDVI and rainfall plots across the zone and in time.

3.4 RELATIONSHIPS BETWEEN NDVI AND RAINFALL BY VEGETATION ZONE.

The transects presented earlier in the discussion of spatial relationships appear to show that the relationship between long-term NDVI and rainfall is much clearer for transects within a single vegetation type (figure 3.2.4) than for transects that span many different types of vegetation (figure 3.2.2). The reason is simply that each vegetation type produces a slightly different NDVI response to rainfall. Therefore, NDVI and rainfall must be compared in terms of plant zone. Monthly rainfall and time-lagged rainfall values

will be compared with monthly NDVI for each vegetative zone. The goodness-of-fit between NDVI and lag rain will be compared between zones, and the controlling time lag will be found for each zone.

The seventy-eight stations were each placed into one of the possible plant zones as described by White (1983). Since only limited first-hand experience about East Africa was available, errors were almost certainly made at this point. No ground-truth data were available. Little or no current information on agriculture, grazing or other human activities near the rainfall stations was available. The dominant vegetation for each station was assumed to be that which was indicated on the UNESCO vegetative mapping, which is not accurate to the 12 km^2 resolution of the data. The dividing lines between the plant zones are not distinct, but are a gradient between the plant types (with the exception of vegetation resulting from unusual soil types, or in the steepest terrain). Several stations were located in the "gray-areas" between plant zones, and were subjectively placed in one of the two zones - this introduces errors into the data set. After the stations were grouped into zones, at least one representative station from each vegetation zone was selected. Determination of the representative station was based on several criteria. Stations well within the vegetation zone were prefered. Stations without a complete rainfall and NDVI data set were disgarded, as were stations near the major towns. In the case of the Coastal forest and Itigi thicket zones, data from only one station

was available, which dictated the use of that station.

The time series of NDVI, rainfall, and 3-month moving average of rainfall for each representative station are shown in figures 3.4.1. The heavy curves represent NDVI, the light solid line shows rainfall, and the light dashed line shows the three-month moving average of rainfall.

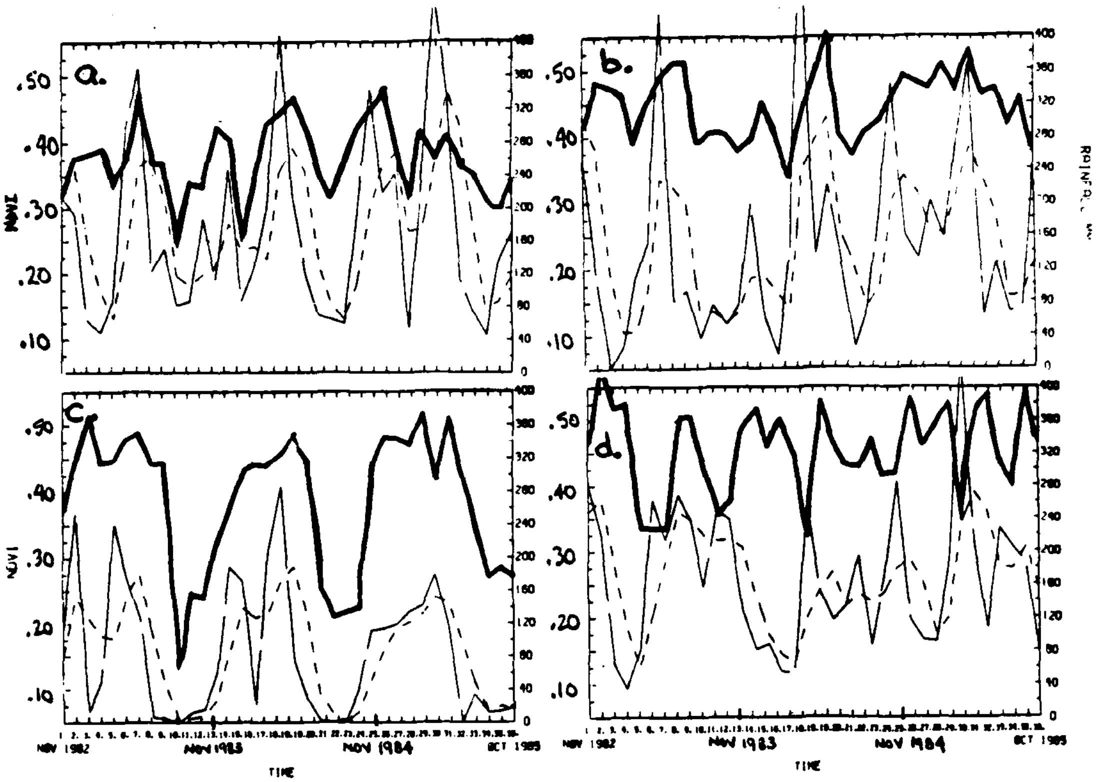
Forest zones. (Figures 3.4.1a - 3.4.1d)

Lowland forest, represented by Bukoba, Tanzania, very rarely experiences dry periods of more than one month. The plant life under these climatic conditions are able to quickly convert rainfall into growth. In many cases, NDVI peaks lag rainfall peaks by zero to one month.

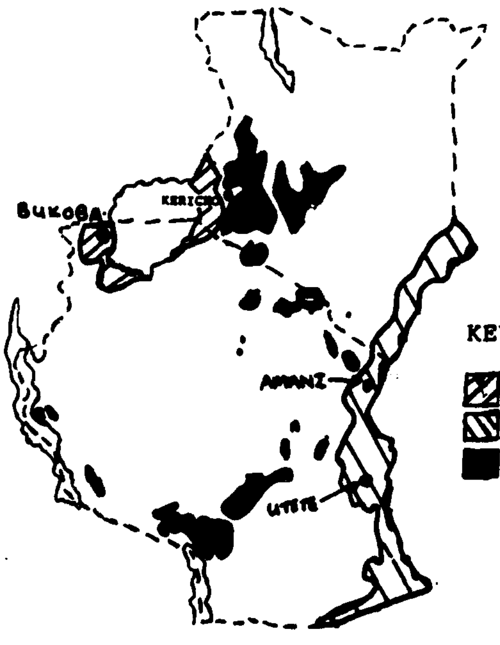
Coastal forest restricted to Amani, Tanzania, do experience months with no precipitation. Plants cannot respond as quickly to rainfall as in the forests on the western shores of Lake Victoria. Within these forest zones, as environmental conditions become drier, plants must make more and more adaptations in response to the increasing aridity. Examples include dormancy, and leaf-dropping and decreased transpiration. Once moisure is supplied, the plant, must alter physiology in order to utilize the moisture - so the conversion of the moisture to greenness takes longer with increasing aridity within the zone.

Coastal forest mosaic (Utete, Tanzania) is a patchwork of settlement, transitional forest and isolated tracts of original coastal forest. The rainfall here is more obviously seasonal, and NDVI peaks seem to lag the rainfall peaks by one to two months.

Upland forest (Kericho, Kenya), shows the effects of a trimodal annual rainfall regime on the NDVI curve. As the forest is evergreen, NDVI values do not show large seasonal fluctuations, remaining close to the mean value. Time lag between peaks is one to two months.



a. Bukoba - Lowland forest
b. Utete - Coastal forest mosaic
c. Amani - Coastal forest
d. Kericho - Upland forest



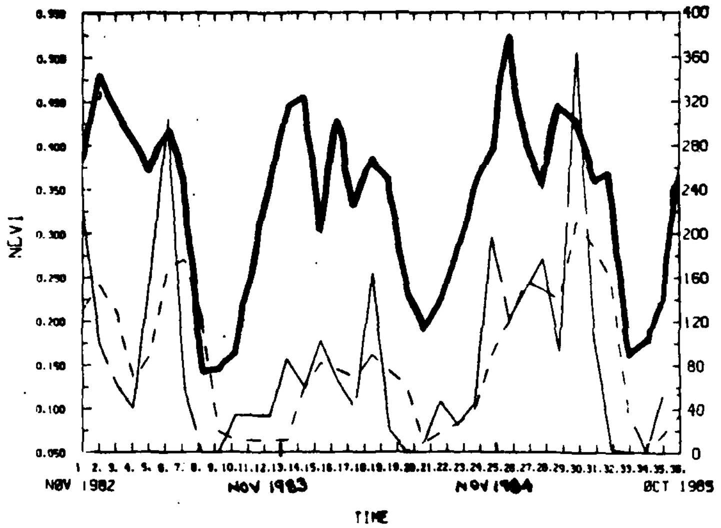
KEY:

Lowland Forest
Coastal Forest Mosiac
Upland Forest

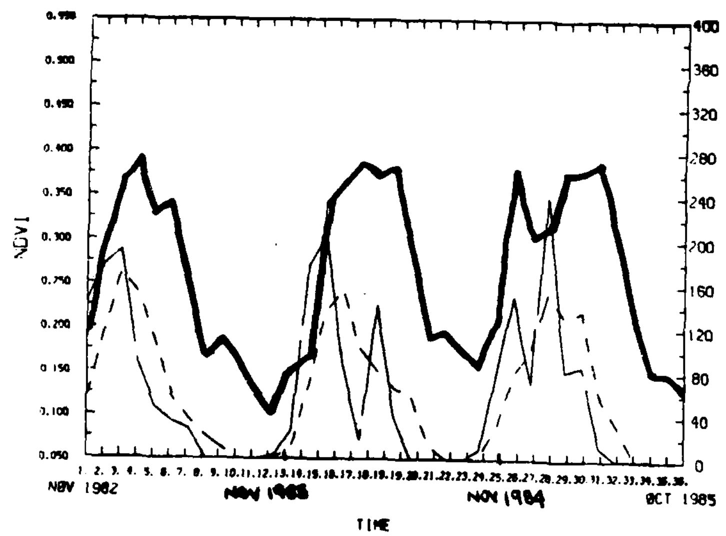
Figures 3.4.1a - 3.4.1d. Forest zones. Time series plot from November 1982 to October 1985 of monthly NDVI, rainfall and three-month moving average of rainfall. (Heavy line is NDVI, dashed line is averaged rainfall). Inset shows the locations of the plant zones and representative stations.

Woodland zones. (Figures 3.4.1e - 3.4.1f)

NDVI shows a large oscillation through the year. Rainfall is highly seasonal - ranging from trimodal in the north to unimodal in southern Tanzania - but all stations have at least one annual long dry season. NDVI peaks seem to lag rainfall peaks by zero to two months. The small green peak occurring during the dry season discussed earlier is absent in the NDVI series of the wet Miombo. There are varying degrees of deciduousness in the Miombo woodlands. The abnormally short dry season at Biharamulo creates a situation where trees are never completely leafless, and where leaf appearance is not as spectacular: therefore, the "green" peak is not present.



e. Biharamulo - Wet Miombo woodland



f. Kondoa - Dry Miombo woodland

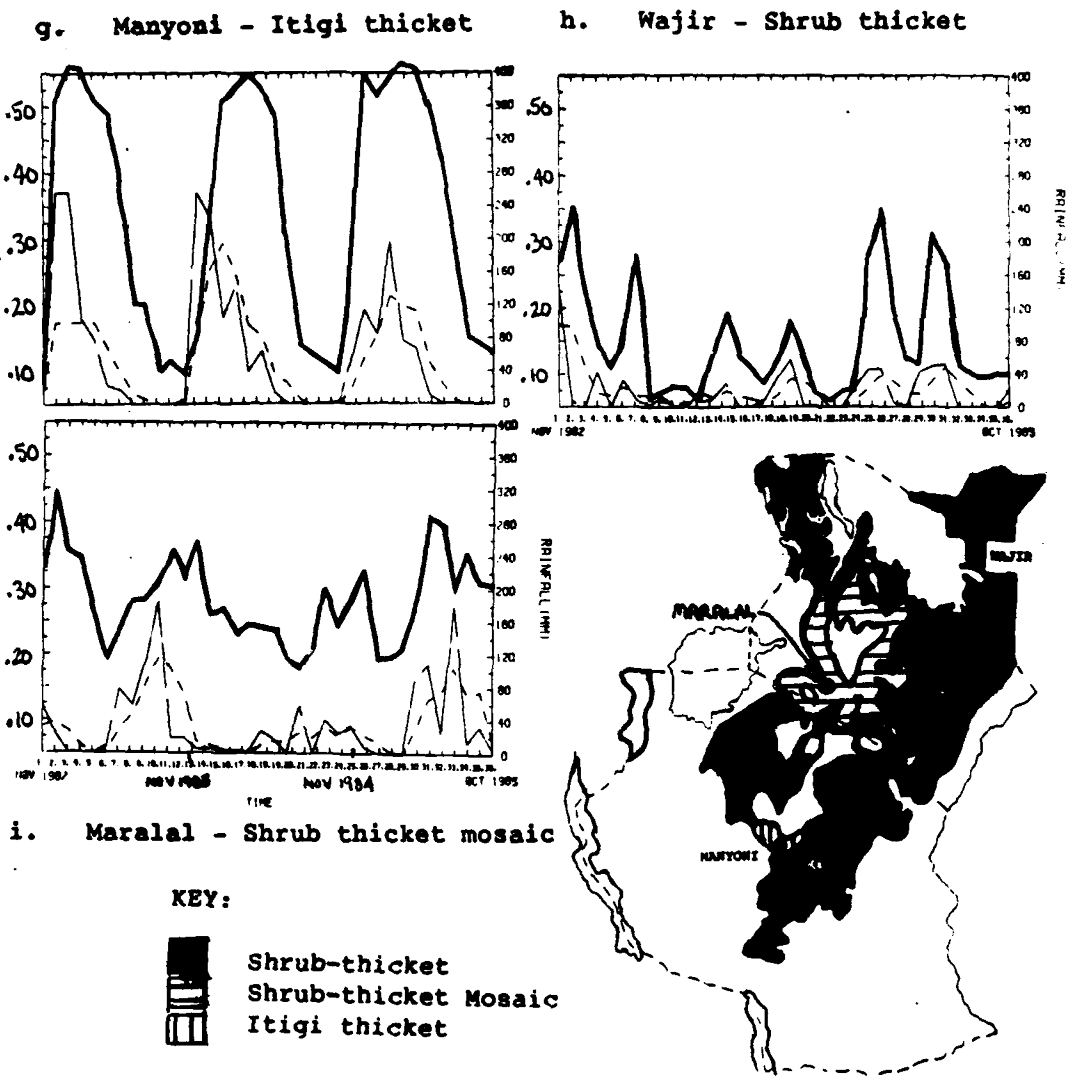
Figures 3.4.1e - 3.4.1f. Woodland zones. Time series plot from November 1982 to October 1985 of monthly NDVI, rainfall and three-month moving average of rainfall. (Heavy line is NDVI, dashed line is averaged rainfall). Inset shows the locations of the plant zones and representative stations.

Thicket zones. (Figures 3.4.1g- 3.4.1i)

The Itigi thicket (Manyoni) is a localized edaphically-induced (e.g., a result of anomalous soils, not climate) plant form. The magnitude of the NDVI changes from dry to wet season are larger here than at any other station - probably due to the very dense growth patterns of the deciduous plants in this zone.

Shrub-thicket (Wajir) covers much of the region, and is a mixture of deciduous shrubs and grass cover. The grass is actively growing and green only during rainy times of the year, and in the drier portions of this zone, the trees are leafless much of the year. Rainfall amounts are generally low with long dry seasons in between the rainy periods. The "sharpness" of the NDVI peaks suggests a very rapid conversion of rainfall to green phytomass, which lasts for only a short time as the soil moisture is quickly utilized and grasses move to a dormant state. The NDVI peak is highest after the short rains which occur late in the year. This is odd, because more total rainfall is received during the long rain season occurring from March to May. This may well be a reflection of more favorable intensity and duration characteristics of the short rains or could possibly be a function of the more favorable seasonal response of the vegetation. The graph suggests a time lag of 0-3 months.

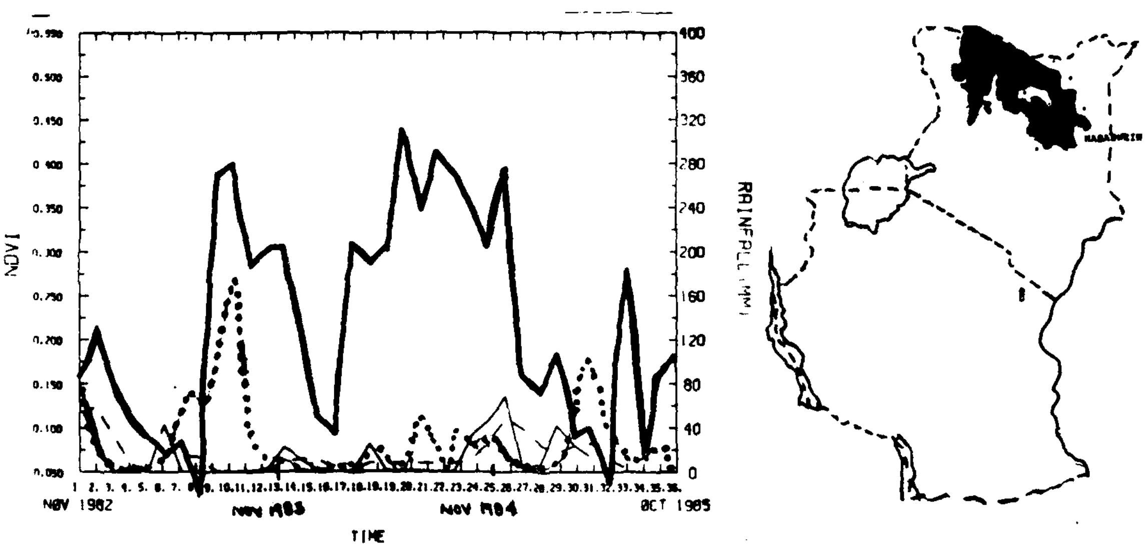
Shrub-mosaic (Maralal) is intermittent between the upland forest and shrub thicket zones in Kenya. The trimodal rainfall regime with shorter dry periods causes a less seasonal NDVI curve than in the drier shrub-thicket zone.



Figures 3.4.1g - 3.4.1i. Shrub thicket zones. Time series plot from November 1982 to October 1985 of monthly NDVI, rainfall and three-month moving average of rainfall. (Heavy line is NDVI, dashed line is averaged rainfall). Inset shows the locations of the plant zones and representative stations.

<u>Semi-desert zone</u>. (Figure 3.4.1j)

Semi-desert shrub (Habaswein) is the zone where the rainfall - NDVI relationship, in theory, should be the clearest. Plants in the driest areas are the best competitors for water. Species survive by rapid intake of water, and the conversion of moisture to phytomass. However, the example for this zone shows the lack of correlation between NDVI and rainfall.



j. Habaswein - Semi-desert shrub

Figure 3.4.1j. Semi-desert shrub zone. Time series plot from November 1982 to October 1985 of monthly NDVI, rainfall and three-month moving average of rainfall. (Heavy line is NDVI, dashed line is averaged rainfall). Inset shows the locations of the plant zone and the representative station.

Habaswein is located on the edge of a seasonal swamp, which is fed by runoff from the northern and eastern slopes of the Kenyan highlands. The abnormally large NDVI values are caused by rain falling in the highlands, and moving in the form of runoff to the

swamp. The dotted line on the graph represents the monthly rainfall reported at a station in the northern Kenyan highlands, and could be used to explain the large NDVI during 1983 at Habaswein. Unfortunately for this study, but not so for the inhabitants, most stations in the driest regions of East Africa are located near permanent water sources. The water is often used for crop irrigation in the area surrounding the rainfall station. The crops create large NDVI values, and the perception of a large NDVI to rainfall ratio, due to the very low naturally-occuring rainfall in this region. The comparison of NDVI and rainfall at non-agricultural stations in this zone should result in strong positive correlations between rainfall and plant response.

To determine the correlation between NDVI and rainfall, and to quantify the lag relationships suggested in figure 3.4.1, simple linear regression was performed of monthly NDVI against the following rainfall lag intervals: 0 month (e.g. rainfall the same month as NDVI); average of two months and one month prior; average of two months, one month, and zero month (3-month moving average); average of one month and zero month; and one month.

To linearize the NDVI - rainfall relationship, a log transform was applied to the data. In some cases, this created more nearly straight-line relationships between NDVI and lagged rainfall (figure 3.4.2). Simple linear regression was performed on NDVI versus the

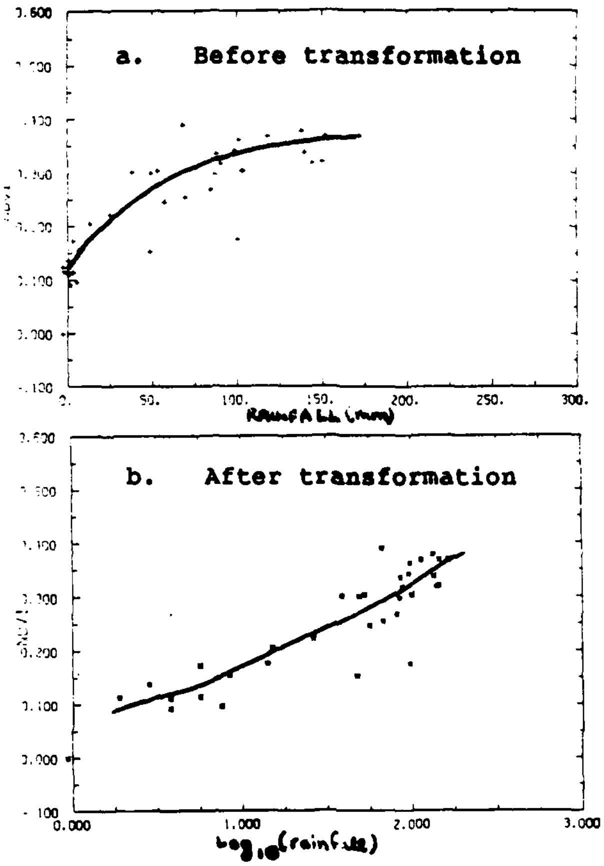


Figure 3.4.2. Sample of the logarithmic transform on the scatter diagrams of monthly NDVI versus rain fall.

transformed and non-transformed lagged rainfalls for each vegetation zone, as well as at least one representative station within each vegetation zone. The rainfall lag giving the largest Pearson product moment coefficient of correlation (r-value) was used as the best-fit. In general, the correlation between NDVI and rainfall by plant zone was good. The best correlation was found for the dry Miombo zone (r=.72). Very good correlations were obtained at individual stations, with r-values at several stations above .80.

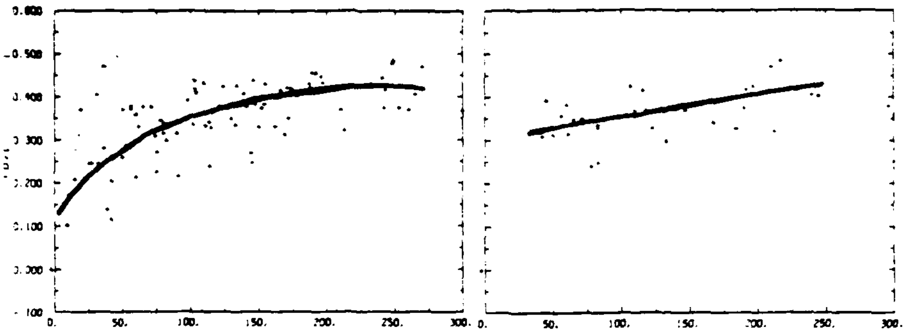
The relationship between NDVI and lagged rainfall was found to be nearly one-to-one for rainfall values less than 50mm to 60mm. Between 50mm and 100mm the relationship gradually erodes. This holds true for most stations and is in agreement with other works (Walter, 1971; Nieuwolt, 1979; Le Houérou, 1984) that compare rainfall and plant growth. Soil readily absorbs up to 50 to 60mm of rainfall per month and this rain is available to the plant for growth; but as monthly rain increases, the portion of the rain going to charge the soil decreases (and the portion going to runoff increases). Above 100mm per month, soils generally become saturated, so additional rains do little for plant growth. In cases of very heavy rainfall (>250mm), NDVI actually decreased with increasing rainfall, which is probably a function of the increased cloudiness accompanying the increased rainfall (which tends to reduce NDVI).

Figure 3.4.3 shows the plots of NDVI against rainfall for each plant zone and representative station. Lines of best fit shown on the plots in figure 3.4.3 are obtained by eye best fit of the data. Table 3.4.1 lists the r-values calculated from the data. The dominant rainfall time lag proved to be the three month moving average, but many zones were best characterized by the average of the two months and one month rainfall. Table 3.4.2 presents the rainfall lag that provides the best correlation for each zone and representative station.

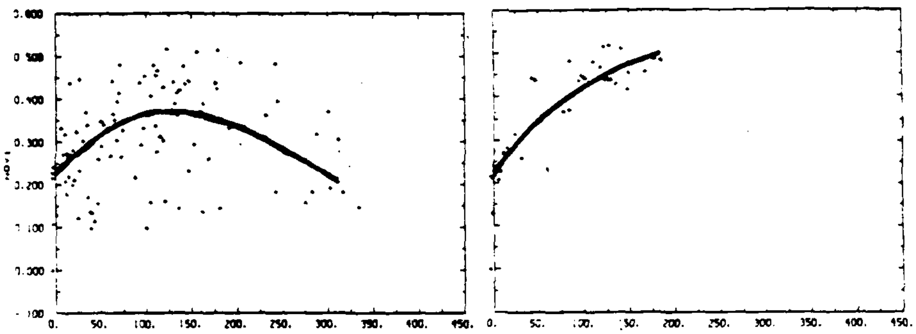
Next, to remove the dependence of the NDVI on a time-lagged rainfall value, the NDVI and rainfall for all 78 stations and

Figures 3.4.3a - 3.4.3j. Scatter diagrams of monthly NDVI versus rain fall for each vegetative zone and representative station. All lines are eye best fit to the data.

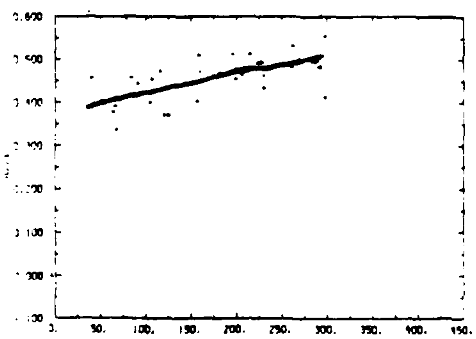
a. **Lowland Forest** **Bukoba**



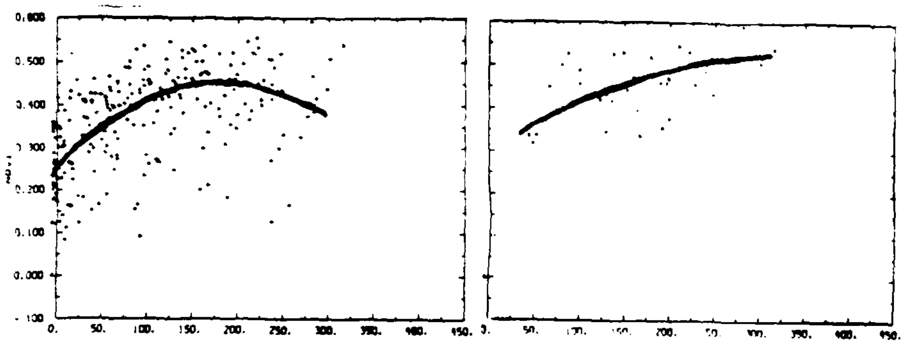
b. **Coastal Forest Mosiac** **Utete**



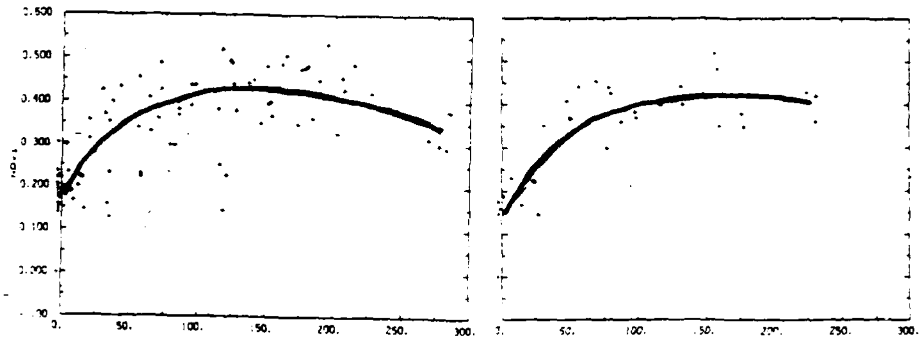
c. **Coastal Forest** **Amani**



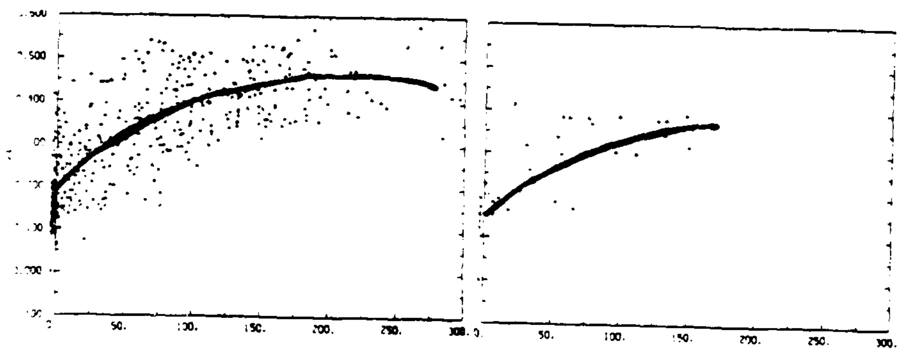
d. **Upland Forest** **Kericho**



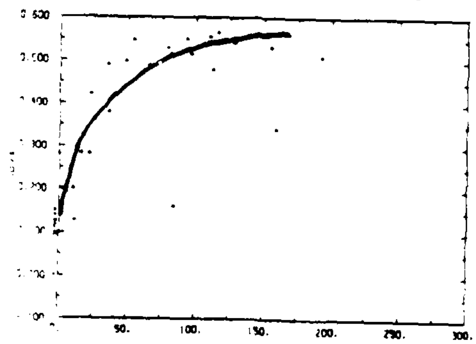
e. **Wet Miombo Woodland** **Biharamulo**



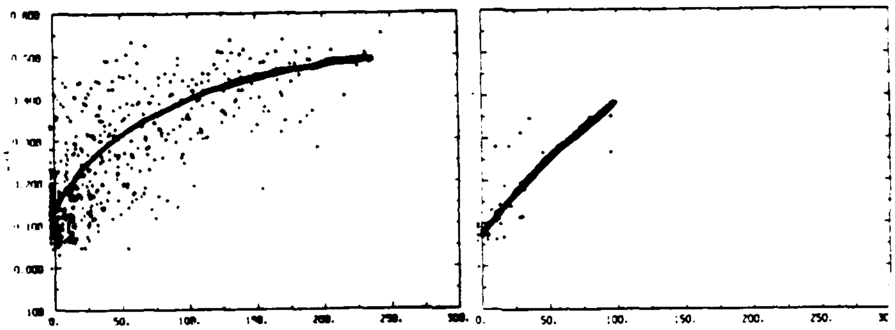
f. **Dry Miombo woodland** **Kondoa**



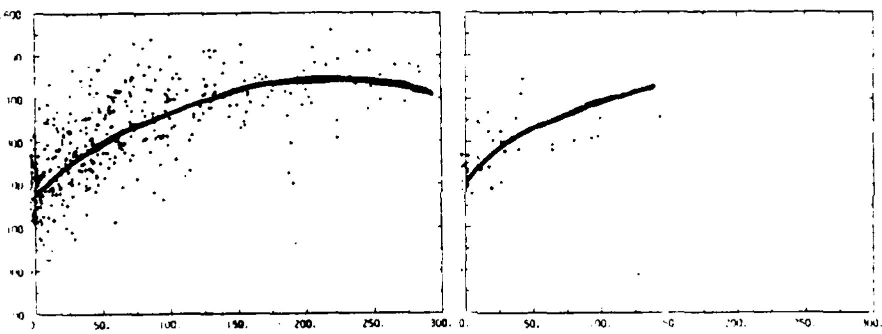
g. **Itigi thicket** **Manyoni**



i. **Thicket mosaic** **Maralal**



h. **Shrub thicket** **Wajir**



j. **Semi-desert shrub** **Habaswein**

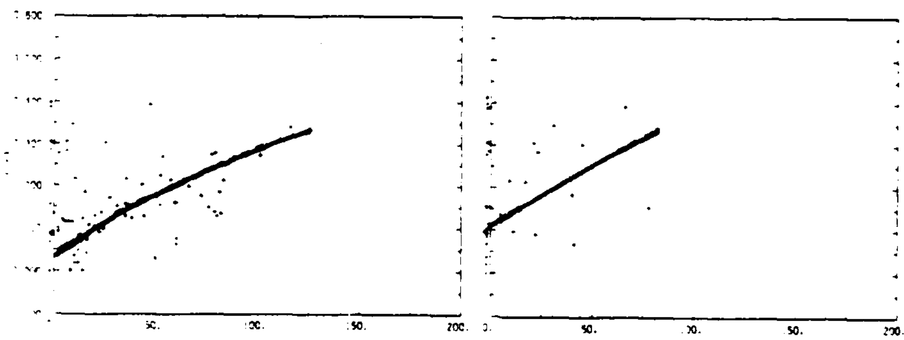


Table 3.4.1 Correlation coefficients calculated for five time lag periods for each vegetative zone and each representative station. All correlation coefficients are positive.

VEGETATION ZONE/STATION		TIME LAG 0	2+1	2+1+0	1+0	1
LOWLAND FOREST	(n=83)	.41	.56	.62	.56	.53
-Bukoba	(n=36)	.57	.22	.49	.53	.28
COASTAL FOREST MOSIAC	(n=102)	.10	.17	.17	.14	.17
-Utete	(n=36)	.53	.79	.87	.74	.71
COASTAL FOREST	(n=36)	.14	.66	.67	.43	.44
UPLAND FOREST	(n=245)	.14	.52	.47	.35	.46
-Kericho	(n=36)	.36	.80	.73	.41	.62
WET MIOMBO	(n=95)	.49	.60	.63	.62	.61
-Biharamulo	(n=33)	.39	.42	.71	.79	.56
DRY MIOMBO	(n=431)	.50	.71	.72	.65	.65
-Mbulu	(n=36)	.35	.74	.74	.58	.60
-Mahenge	(n=36)	.66	.76	.81	.76	.71
ITIGI THICKET	(n=33)	.40	.75	.74	.60	.62
SHRUB-THICKET	(n=507)	.46	.68	.72	.66	.64
-Wajir	(n=36)	.47	.61	.71	.66	.65
-Mpwapwa	(n=36)	.67	.87	.91	.85	.81
SHRUB-THICKET MOSAIC	(n=413)	.30	.63	.64	.52	.57
-Maralal	(n=32)	.17	.53	.47	.41	.50
SEMI-DESERT SHRUB	(n=64)	. 0	.10	.22	.17	.10
-Habaswein	(n=25)	.10	.11	. 0	. 0	. 0

Table 3.4.2. Summary of the optimal time lag for the NDVI - rainfall relationship by each vegetative zone and each representative station.

VEGETATION ZONE/STATION	RAINFALL LAG(months) 0	2+1	2+1+0	1+0	1
Lowland Forest			X		
-Bukoba	X				
Coastal Forest Mosaic			X		
-Utete			X		
Coastal Forest			X		
Upland Forest		X			
-Kericho		X			
Wet Miombo			X		
-Biharamulo				X	
Dry Miombo			X		
-Mbulu			X		
-Mahenge			X		
Itigi Thicket		X			
Shrub-Thicket			X		
-Wajir			X		
-Mpwapwa			X		
Shrub-Thicket Mosiac			X		
-Maralal		X			
Semi-Desert Shrub			X		
-Habaswein		X			

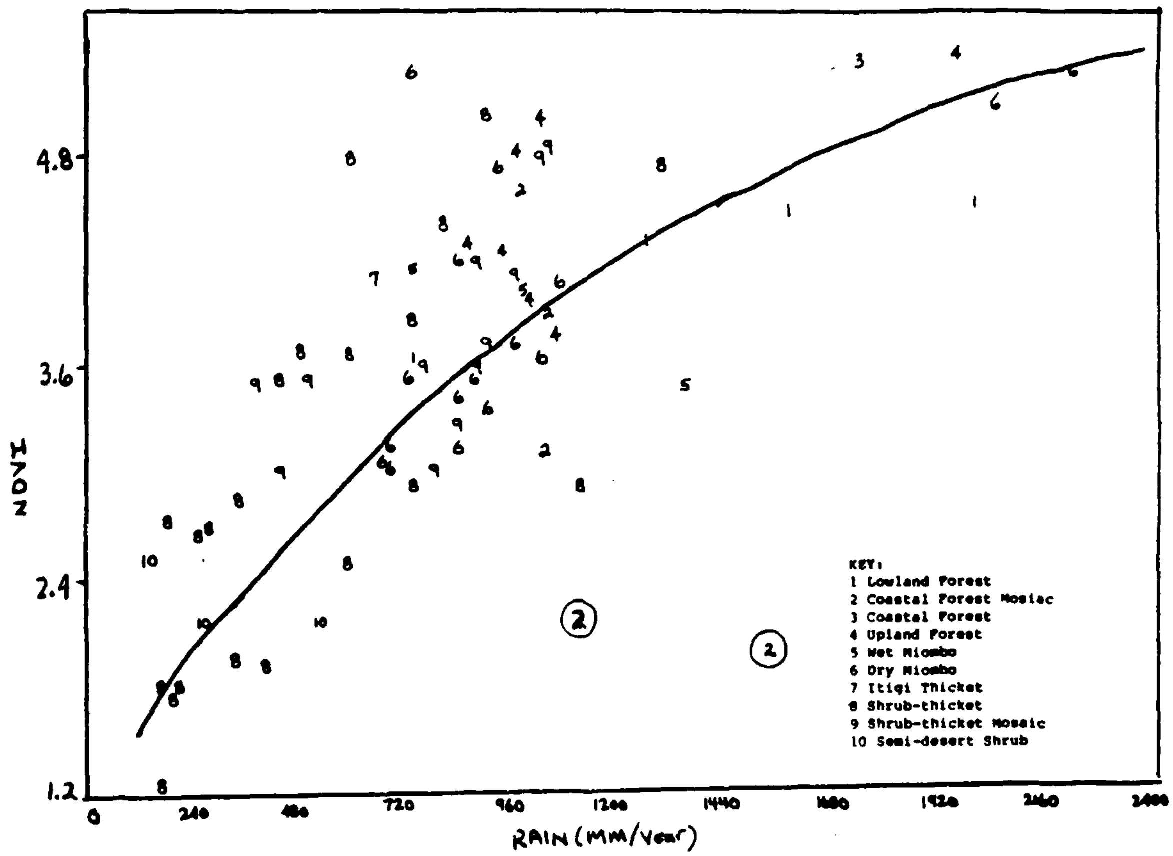
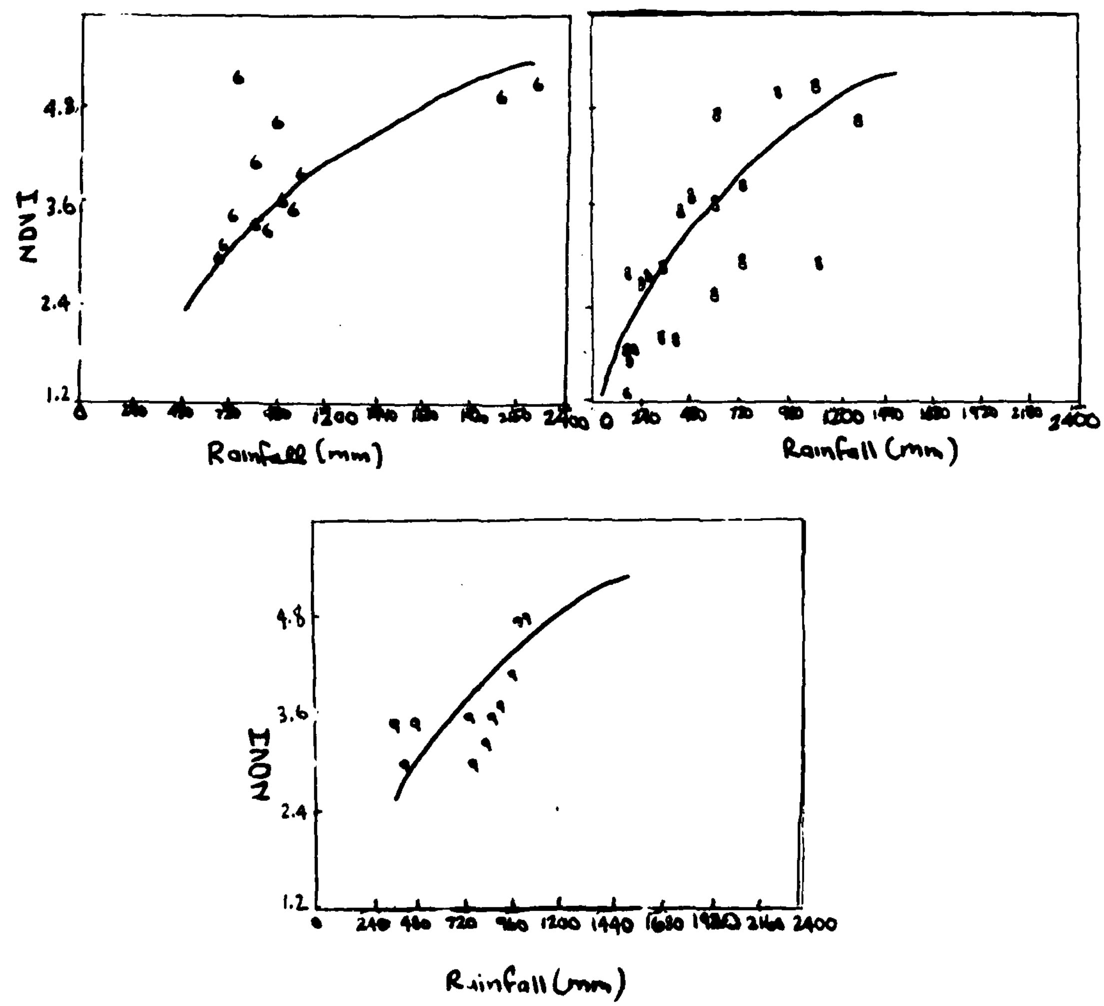


Figure 3.4.4. Plot of the three-year average of NDVI and rainfall. Numbers represent the plant zone.

a. Dry Miombo zone

b. Shrub-thicket zone



c. Shrub-thicket mosiac zone

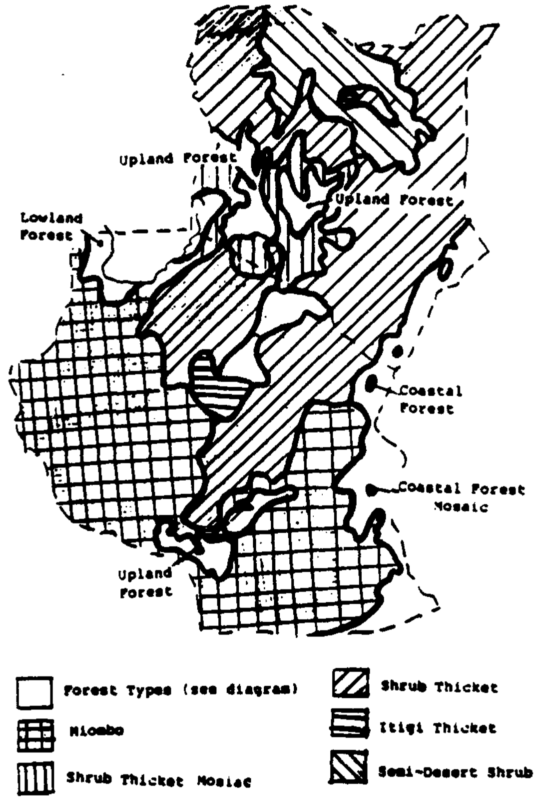
Figure 3.4.5. Plot of the three-year average of NDVI and rainfall for selected plant zones.

selected vegetation zones were averaged over the three year period. The resulting scatter diagram of the three-year averages of NDVI and rainfall is shown in Figure 3.4.4. The r-value obtained for all 78 stations with no data removed was .57, which indicates a fair correlation between NDVI and rainfall. When the extreme data points (circled values in figure 3.4.4) are removed, the correlation coefficient increases to r=.73. The data are removed because of the abnormally low NDVI/rainfall ratios: both of these stations are located on the coast of the Indian Ocean, and the composited NDVI values are probably reduced by the effects of the water surface (NDVI of water is essentially zero). A similar correlation between NDVI and effective rainfall produces a r-value of .71.

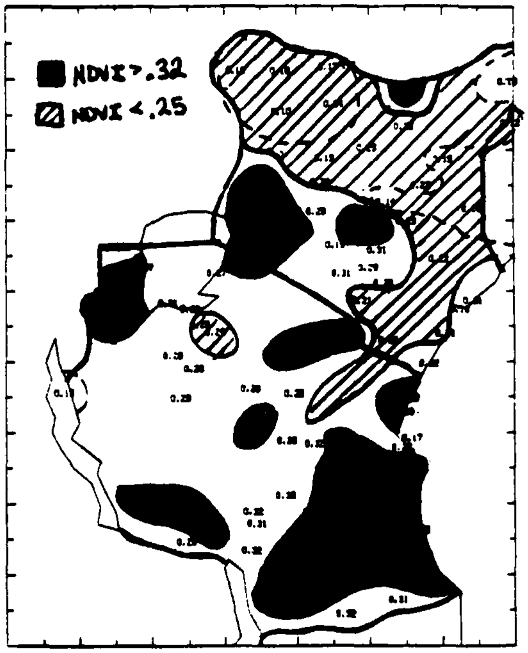
Highlighted in figure 3.4.5 are the eye best fit curves for the plot of three-year average of rainfall versus NDVI for the dry Miombo, shrub-thicket, shrub-thicket mosaic vegetation zones. The long-term averages of rainfall correlate well with long-term NDVI in these plant zones.

3.5 MAPPING OF VEGETATION.

As discussed earlier, researchers have demonstrated a clear relationship between yearly integrated NDVI and the amount of accumulated above-ground green phytomass, which is very similar to primary production (Tucker *et al.*, 1985b). Using published estimates of average primary production for the world's major plant zones, annually-integrated NDVI can be used to create an inexpensive and reasonably accurate vegetative mapping scheme. Tucker *et al.* (1985b) used this



a. UNESCO mapping (from White, 1983)



b. Mapping based on average annually-integrated NDVI for 1983-1985.

Figure 3.5.1. Comparison of vegetative mapping schemes.

scheme to map the vegetation of the African continent (for discussion, see page 13). This mapping is a good approximation of vegetative mapping created by the more conventional means; namely, the combination of surface and aerial surveys. When Tucker's mapping scheme is applied to the three-year average NDVI data, a reasonably accurate vegetation mapping is produced (figure 3.5.1). The most obvious relationships are the high NDVI values indicative of the high primary production in the upland forest region, and the lowest NDVI reflecting the low production in the semi-desert interior of Kenya.

However, notice the lack of resolution between the deciduous Miombo woodland and the coastal forest of southeastern Tanzania. Because annual primary production is similar for both plant zones, the two physiologically- distinct vegetation zones are indistinguishable.

Norwine and Greegor (1983), in a similar study, use a factor of rainfall and NDVI in characterizing plant zones in Texas. Le Houérou (1984), discusses the concept of rain use efficiency, which is defined as the amount of above-ground phytomass produced per hectare per year per millimeter of rain. The plants in various vegetation zones each should have a different physical response to rainfall. Because competition for soil moisture becomes less intense with increasing annual rainfall, plants in wetter vegetation zones can be more wasteful with rainfall, and few plant species have physiological means to limit water loss through transpiration or have intricate root systems for efficient uptake of water. The opposite is true in desert and semi-desert regions, where special strategies have developed to deter the effects of drought, and where the little rain that falls is efficiently converted to phytomass.

Since the plants in different vegetative zones respond differently to the same amount of rainfall, remote sensing is applied to the rain use efficiency concept to produce the rain-greenness ratio (RGR). The RGR is a ratio of the three-year average of annually-integrated NDVI/rain (mm) multiplied by a constant to produce values ranging from 0-10. A low RGR value suggests that the vegetation converts little water to phytomass, while a high RGR indicates effi-

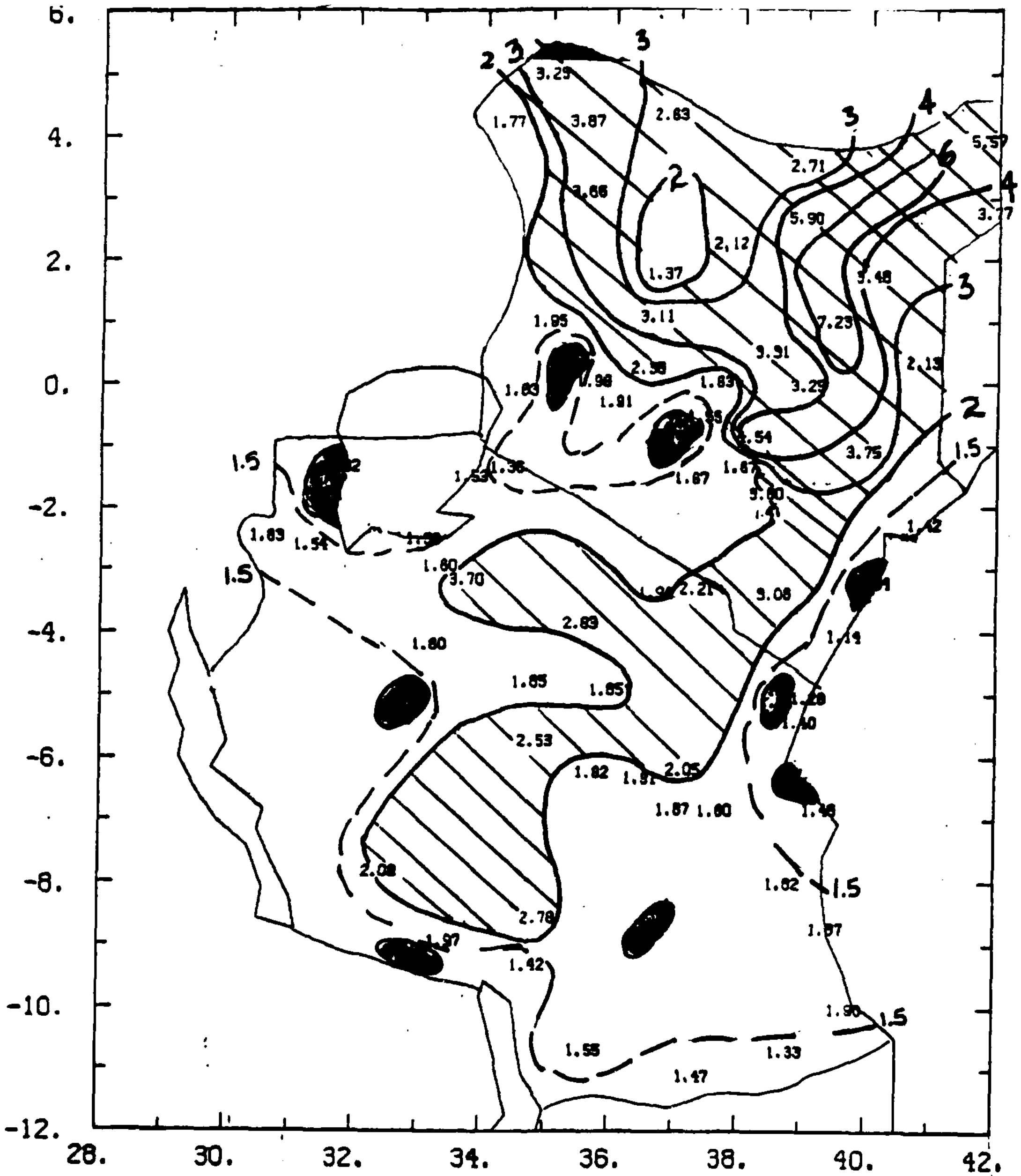
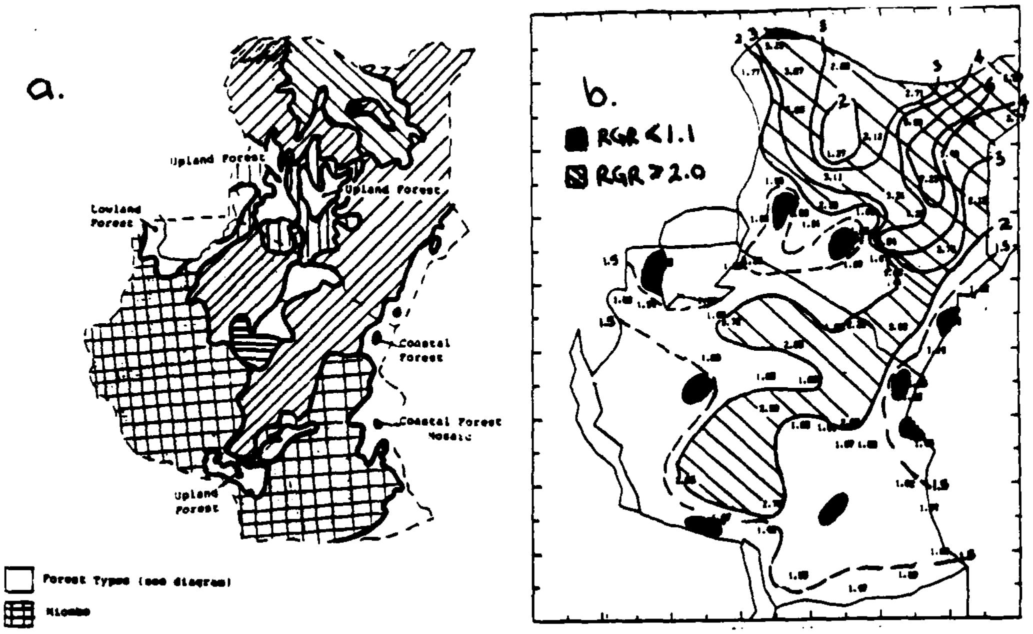
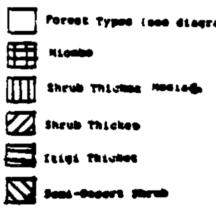


Figure 3.5.2. Plot of Rain Greenness Ratio data (for 1983-1985). Shaded areas indicate values < 1.1, stippled areas enclose values > 2.





a. UNESCO mapping (from White, 1983)
b. Mapping using Station Rain Greenness Ratio (RGR) data for 1983-1985.

Figure 3.5.3. Comparison of vegetative mapping schemes.

cient water use. Figure 3.5.2 shows the mapping produced when the RGR data are plotted. The analysis of the data produces a mapping that appears to be far superior to a mapping that considers only annually-integrated NDVI.

Figure 3.5.3 compares the RGR plot to the UNESCO vegetation map. The lowest RGR values (< 1.1) correspond well with the upland, lowland, and coastal forest zones shown on the UNESCO mapping. The deciduous Miombo vegetation zone is now differentiated from the coastal forest zone in southeastern Tanzania by the 1.5 RGR iso-

pleth. The stippled area on the RGR map (RGR > 2.0) corresponds well with the boundries of the large shrub-thicket zone on the UNESCO mapping. Overall, the RGR analysis provides a very close facsimile of the zone in the UNESCO mapping. This is a very promising application of remote sensing to vegetative mapping that should be pursued in future works.

4. CONCLUSIONS

Several NDVI time series were presented in order to illustrate the complexity of NDVI. These examples show the effects of rainfall seasonality and amount, and other environmental factors on NDVI, through variation of the appearance of the NDVI time series at stations within the same plant zone and through the similarity of NDVI time series in two distinct time zones (but in similar rainfall regimes). The spatial dependence of NDVI on rainfall was introduced through regional plots of monthly and yearly NDVI and rainfall. The areas with the highest rainfall in general had the largest NDVI values. The temporal link between NDVI and rainfall was established by presenting the relative differences of NDVI and rainfall between consecutive wet and dry Decembers. This example clearly showed the region-wide dependence of NDVI on rainfall, because the largest relative changes in rainfall tended to occur with the largest relative changes in NDVI. Month-to-month trends in average rainfall and NDVI across surface transects show a good relationship between anomalous rainfall conditions and NDVI response.

Through initial inspection of time series plots of monthly NDVI, rainfall and average rainfall, it was found that different plant communities respond differently to rainfall - due in part to the variable physical characteristics of the vegetation types in the

region. For this reason, the comparison of monthly rainfall and NDVI was analyzed by plant zone. The correlation of the data was limited to simple linear regression between monthly NDVI and several time lag rainfall values. In general, r-values obtained for plant values were good (ranging from r=.22 to r=.72), with overall high r-values at representative stations within the plant zones (ranging from r=.11 to r=.91). When the three-year averages of NDVI against rainfall for all stations are plotted, a good correlation is found; and when anomalous stations are removed, the correlation improves.

The long-term average of integrated NDVI was shown to be useful in mapping the location of major plant types. This mapping technique was improved through consideration of the physical characteristics of plants in response to moisture. This rain-greenness relationship should be tested in other parts of Africa and in the remainder of the world to determine its validity and applicability.

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